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ORIGINAL ARTICLE

Microbial-induced carbonate precipitation (MICP) technology: a review on the fundamentals and engineering applications

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Abstract
The microbial-induced carbonate precipitation (MICP), as an emerging biomineralization technology mediated by specific bacteria, has been a popular research focus for scientists and engineers through the previous two decades as an interdisciplinary approach. It provides cutting-edge solutions for various engineering problems emerging in the context of frequent and intense human activities. This paper is aimed at reviewing the fundaments and engineering applications of the MICP technology through existing studies, covering realistic need in geotechnical engineering, construction materials, hydraulic engineering, geological engineering, and environmental engineering. It adds a new perspective on the feasibility and difficulty for field practice. Analysis and discussion within different parts are generally carried out based on specific considerations in each field. MICP may bring comprehensive improvement of static and dynamic characteristics of geomaterials, thus enhancing their bearing capacity and resisting liquefication. It helps produce eco-friendly and durable building materials. MICP is a promising and cost-efficient technology in preserving water resources and subsurface fluid leakage. Piping, internal erosion and surface erosion could also be addressed by this technology. MICP has been proved suitable for stabilizing soils and shows promise in dealing with problematic soils like bentonite and expansive soils. It is also envisaged that this technology may be used to mitigate against impacts of geological hazards such as liquefaction associated with earthquakes. Moreover, global environment issues including fugitive dust, contaminated soil and climate change problems are assumed to be palliated or even removed via the positive effects of this technology. Bioaugmentation, biostimulation, and enzymatic approach are three feasible paths for MICP. Decision makers should choose a compatible, efficient and economical way among them and develop an on-site solution based on engineering conditions. To further decrease the cost and energy consumption of the MICP technology, it is reasonable to make full use of industrial by-products or wastes and non-sterilized media. The prospective direction of this technology is to make construction more intelligent without human intervention, such as autogenous healing. To reach this destination, MICP could be coupled with other techniques like encapsulation and ductile fibers. MICP is undoubtfully a mainstream engineering technology for the future, while ecological balance, environmental impact and industrial applicability should still be cautiously treated in its real practice.

Keywords Biomineralization · MICP · Engineering application · Microbial-induced carbonate precipitation · Calcium carbonate · Biogeotechnical engineering

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Introduction

The first two decades of the twenty-first century have witnessed the rapid growth of global economy. Infrastructure construction, as a foundation for the developing economy, has been paid great attention to by countries all over the world, especially developing countries with huge populations. As the construction activities of human beings become more and more frequent and intense, engineering problems keep emerging in an endless stream. Among these problems, some have been commonly acknowledged as world-wide challenges, such as soil liquefaction mitigation, water resources protection, structural rehabilitation, slope stabilization, erosion control, and hazardous waste disposal (U. E. P.2008; Osinubi et al. 2020; Yu et al. 2020). However, although experts and engineers have tried many approaches to solve these existing challenges, many of them still remain too interrelated and far-reaching to be understood and handled via knowledge and methods within a single discipline (DeJong et al. 2011; Jiang et al. 2020), setting the interdisciplinary approach a priority for scientists and engineers. On the other hand, after the outbreak of the COVID-19 pandemic, the world calls for safer, more efficient and greener technologies and adaptation strategies in civil, geotechnical and geoenvironmental infrastructures (Tang et al. 2020a). Meanwhile, these novel engineering technologies, which are promising for the future, have been embraced globally within the frame of Sustainable Development Goals (Fig. 1).

In recent years, there are more and more discussions about applying biological processes in engineering. Biogeotechnical engineering, a new paradigm requiring multidiscipline thinking, embraces biology, geochemistry and geomechanics (DeJong et al. 2013). Amongst lots of biogeotechnical engineering technologies, microbial-induced carbonate precipitation (MICP) acts as an innovative sustainable biomineralization technology (Fig. 1) and attracts wide attentions due to its feasibility and convenience in various fields (Chu et al. 2011; Liu et al. 2021a, b; Martinez et al. 2021; Zeng et al. 2021), including geotechnical engineering, hydraulic engineering, geological engineering, ocean engineering, and environmental engineering (Terzis and Laloui 2019; Cheng et al. 2021; Matsubara 2021; Sharma et al. 2021). The MICP technology makes use of specific strains of bacteria which widely exist in nature and can deposit calcium carbonate through metabolic activities (Ramakrishnan et al. 2001; Dhami et al. 2013; Salifu et al. 2016; Gardoso et al. 2020). These calcium carbonate crystals showing high strength and stable properties have the ability to fill gaps between particles, bind them together and then cement materials (Fig. 2). Therefore, the MICP technology has been utilized to prevent liquefication of sandy soil, manage the leakage of containers, repair cracks in structures, mitigate seashore erosion, slope

Fig. 1 Relationships between Sustainable Development Goals (published by United Nations Department of Global Communications) and the engineering technology (e.g., MICP), explaining existing problems and main challenges

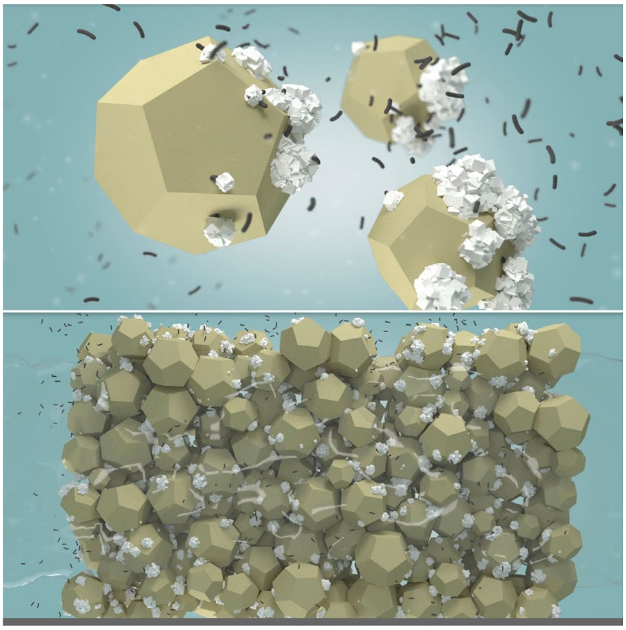


Fig. 2 Schematic representation of bacteria cells (black) attaching on soil grains (brown) and inducing the formation of calcite crystals(white); system of grains (top) and porous assembly of soil grains (bottom) (Terzis 2017)

failure and heavy metal contamination, etc. (Chu et al. 2013; Liu et al. 2020a; Tang et al. 2020b; Meng et al. 2021a, b). Compared with traditional engineering technologies, like compaction by rollers or densification by vibroflotation, the MICP technology has less physical impact on the environment. For example, when carrying out biogrouting on site, only small injection and extraction wells need to be drilled and pumping equipment needs to be installed (van Paassen 2011). Compared with conventional chemical grouting technologies, the bacteria and cementation solutions employed by MICP have lower viscosity and can infiltrate into earth materials more easily (Chu et al. 2012), making deeper and thicker cementation possible (Ivanov and Chu 2008). Moreover, the mechanical/hydraulic properties of materials improved by MICP also maintain extraordinary durability (Ramakrishnan et al. 2005).

Carbonate precipitation could be achieved through many different biological or biomineralization processes, including ureolysis (Yu et al. 2020), denitrification (Pham et al. 2016; Hamdan et al. 2017; O'Donnell et al. 2019), sulphate reduction (Warthmann et al. 2000; Le Pape et al. 2017; Hwang et al. 2018; Gu et al. 2019), and iron reduction (Ivanov et al. 2010; Weaver et al. 2011; Zeng and Tice 2014). Enzymatic hydrolysis process of urea has attracted the widest attention because of its high energy efficiency, low cost, controllable reaction process, and direct separation and harvest procedure (DeJong et al. 2010). The key part of the enzymatic hydrolysis process of urea is the catalytic effect of urease produced by specific bacterial strains. Fujita et al. (2000) firstly found the correlation between calcium precipitation rate and urea hydrolysis rate. Among all urease-producing bacteria strains, *Sporosarcina pasteurii* (ATCC 11859), a bacterium isolated from soils, is generally considered to catalyze urea hydrolysis at the highest rate (Terzis and Laloui 2019). Compared with other bacteria strains, *Sporosarcina pasteurii* is more adaptable to the environment (Kannan et al. 2020). In addition, *Sporosarcina pasteurii* appears to be high-yielding and efficient in calcium carbonate producing. The mechanism of MICP through urea hydrolysis process is that urea can be decomposed into CO_2 and NH_3 by urease secreted from the bacteria cells (Eqs. (1), (2)). During the urea hydrolysis process, bacteria can also utilize urea as their energy and nitrogen source for respiration, where CO_2 is also produced. In alkaline environment caused by NH_3 (Eq. (3)), CO_2 is converted into ${CO_3}^{2-}$ (Eq. (4)). At the same time, bacteria are able to absorb Ca^{2+} from the surrounding environment onto their cell surfaces with negative charge (Fig. 3a). Then, when Ca^{2+} encounters ${CO_3}^{2-}$, large quantities of calcium carbonate crystals form and deposit on the surface of the bacteria cells (Fig. 3b), resulting in bonding granular particles and filling internal pores and cracks of materials (Eq. (5)) (De Muynck et al. 2010a; Montoya et al. 2013; Qian et al. 2015; Jiang 2021).

$$CO(NH_2)_2 + H_2O \overset{Urease-producing\ Bacteria}{\rightarrow} NH_3 + H_2NCOOH(1) \tag{1}$$

$$H_2NCOOH \rightarrow NH_3 + CO_2(2) \tag{2}$$

$$NH_3 + H_2O \rightarrow NH_4^+ + OH^-(3) \tag{3}$$

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^- \rightarrow 2H^+ + CO_3^{2-} \tag{4}$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \tag{5}$$

This paper aims at reviewing geo-engineering applications of the ureolysis-based MICP technology, from an interdisciplinary perspective of biology, geochemistry, geomechanics, hydrology, geology, and environmental engineering (Fig. 4). More specifically, this paper covers the applications of MICP in geotechnical engineering, construction materials, hydraulic engineering, geological engineering, and environmental engineering with a focus on the implementation, efficiency, cost/viability and environmental impacts of the MICP technology in these fields. In addition, the future opportunities and challenges for engineering applications of MICP are also discussed.

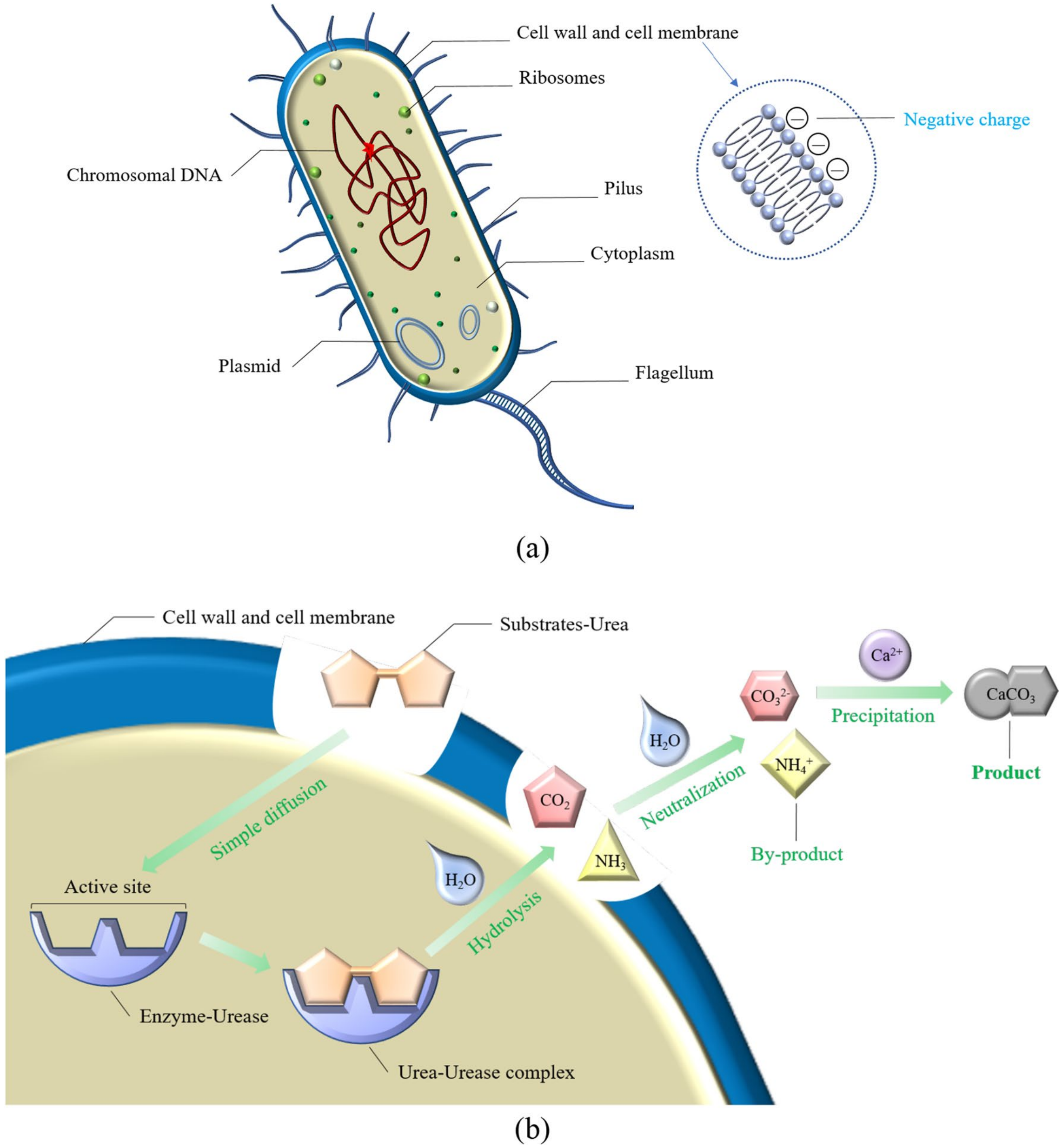
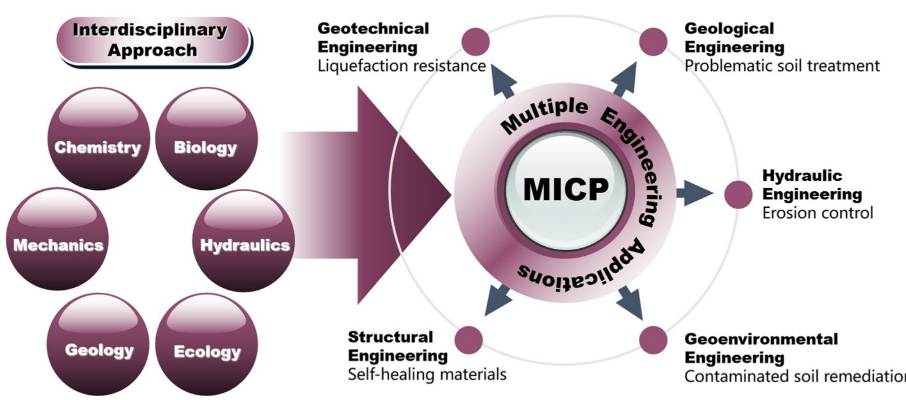


Fig. 3 Schematic drawing for the MICP process: (**a**) Cell membrane of *Sporosarcina pasteurii*; (**b**) Principles of the MICP reaction

Fig. 4 Schematic drawing for the interdisciplinary approach of this review



Geotechnical engineering

The concept of bio-mediated geotechnical engineering was firstly proposed at the end of the twentieth century (Stocks-Fischer et al. 1999; Fujita et al. 2000). Particularly, the MICP technology has received the greatest research focus in the community of geotechnical engineering since then. Generally, MICP seems to be versatile in the field of geotechnical engineering. In this part, several typical applications of the MICP technology in geotechnical engineering are reviewed with a focus on the extent to which this technology can improve the macro-scale mechanical properties of geomaterials.

Enhancing soil bearing capacity

Like many other thriving engineering technologies, the MICP technology is faced with the challenge of up-scaling implementation when it comes to improving the mechanical properties of soils, such as bearing capacity. According to MICP trials at the laboratory scale, common agreement has been reached among researchers that current knowledge provides with the necessary proof of concept and establishes sufficient basis for performing it in field-scale, real applications. Basically, the unconfined compressive strength (UCS) has a positive relationship with the bearing capacity of soils, thus is commonly used to reflect it (Choi et al. 2020). Figure 5 shows the compiled data on the relationships between the cementation content (δ) and

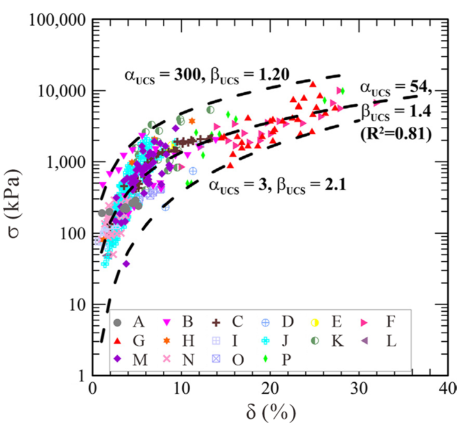


Fig. 5 Relationships between the unconfined compressive strength (σ) and the calcium carbonate content (δ) (α_{UCS} and β_{UCS} are the empirical fitting parameters) ([**A**] Whiffin et al. 2007; [**B**] Cheng et al. 2013; [**C**] Zhao et al. 2014; [**D**] Choi et al. 2016a; [**E**] Choi et al. 2017a; [**F**] GGNN and Kawasaki 2017; [**G**] van Paassen et al. 2010; [**H**] Shanahan and Montoya 2014; [**I**] Soon et al. 2014; [**J**] Cheng et al. 2017; [**K**] Gomez and DeJong 2017; [**L**] Li et al. 2018b; [**M**] Qabany and Soga 2013; [**N**] Cheng et al. 2014; [**O**] Choi et al. 2016b; [**P**] Danjo and Kawasaki 2016) (Modified from Choi et al. 2020)

UCS (σ) of the MICP treated sand from different literatures, which could help understand the potential of MICP to boost the biochemical reactions and add to the bearing strength of soils (Eq. (6)).

$$\sigma[\text{kPa}] = \alpha_{UCS} \cdot \left(\frac{\delta}{1\%}\right)^{\beta_{UCS}} (6) \tag{6}$$

Attempts have been carried out referring to various schemes designed for the field-scale MICP treatment to enhance the bearing capacity of soils (Fig. 6). The most common approach for large-scale MICP treatment is bioaugmentation (Mujah et al. 2017; Xiao et al. 2019b; Jain and Arnepalli 2019). A test was designed to further evaluate the process of biogrouting in sand filled boxes of 1 m^3, simulating a single point injection (van Paassen et al. 2009). Then, a pilot test injecting *Sporosarcina pasteurii* into fine sand placed in a 100 m^3 scale was performed (van Paassen et al. 2010). Results showed that bacteria could disperse over a long distance in sand, which showed feasibility for calcifying sand and enhancing it in-situ. Remarkably, the resulting strength was up to 12 MPa. Li (2014) also used this grouting method to solidify 1 m^3 sand body. The difference was that multiple grouting ports and extraction ports were set on both sides of the 1 m^3 model. The cementation efficiency was as high as 93%, the average $CaCO_3$ content was 4.55% (mass percentage), and the UCS was 1.0 ~ 1.4 MPa.

Meanwhile, steps towards up-scaling MICP technology for soil-strengthening are not limited to bioaugmentation. It is also promising to encourage the growth of indigenous alkalinity-tolerant and urease-producing microorganisms within the geomaterial using nutrient solution and calcium source. This approach is known as biostimulation (Crawford et al. 2013; Wang et al. 2020). Gomez et al. (2017) conducted a large-scale biocementation experiment to evaluate the differences in improvement of geotechnical properties obtained using a bioaugmentation approach with *Sporosarcina pasteurii* and a biostimulation approach, which stimulated native urease-producing bacteria strains for MICP. They prepared two 1.7-m-diameter 0.3-m-thick soil tank specimens using two different approaches and treated them over twelve days. Nonuniform spatial distribution of improvement was observed. Highly cemented regions achieved shear wave velocities over 960 m/s and the increase in cone tip resistances of over 419%, demonstrating that biostimulation is comparable to bioaugmentation in improvement at the meter scale. The use of the stimulation approach is considered to bring significant reductions in environmental and ecological impacts and anticipated treatment costs (Gomez et al. 2014; Jiang et al. 2020). But considering the whole life cycle of MICP, the total environmental impact and economic cost are hard to be precisely

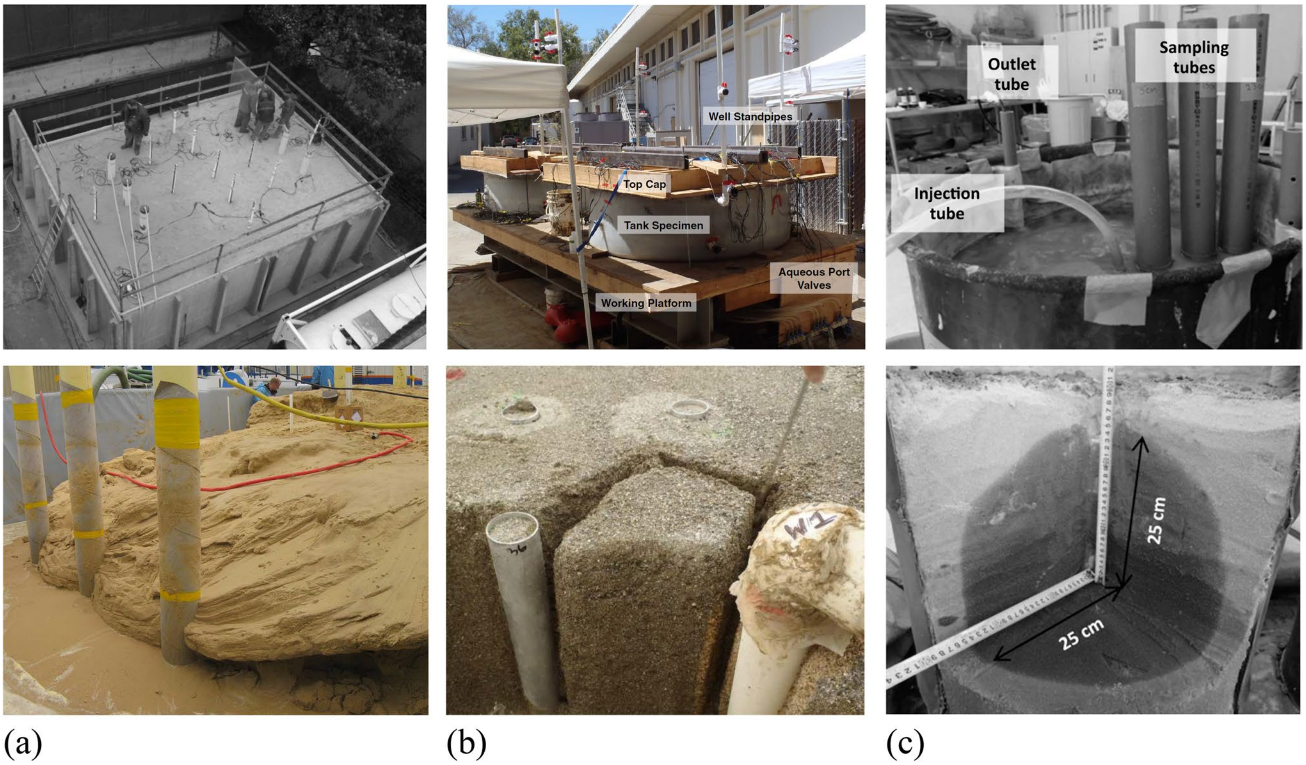


Fig. 6 Large-scale MICP cementation experiments to enhance the bearing capacity of soils, with set-up (top) and cemented sample (bottom): (**a**) Through bioaugmentation (van Paasen et al. 2010); (**b**) Through biostimulation (Gomez et al. 2017); (**c**) Through enzymatic approach (Neupane et al. 2013)

estimated (Porter et al. 2021). Enzyme induced carbonate precipitation (EICP), the $CaCO_3$ precipitation technology using purified enzyme directly, is also worth considering. It is more straightforward than using bacteria, because the cultivation and the fixation of bacteria (i.e., biological treatment) are not necessary (Yasuhara et al. 2012). A precipitation ratio up to 80% could be obtained using a small amount of the enzyme (2.0 g/L) and the stiffness of samples obtained from large-scale samples showed the efficacy of this EICP technique for in-situ applications (Neupane et al. 2013).

One challenge for engineering application of the MICP process is the overall cost, including biomass production and recovery of by-product (e.g., ammonium ion and ammonia). However, for a range of UCS lower than 500 kPa, the cost of MICP was comparable with techniques such as jet grouting, laying a firm foundation for optimizing MICP process for economical usage in enhancing bearing capacity in the field (Filet et al. 2012). Similarly, possible replacement of costly yeast extract, which is commonly used for the growth of *Sporosarcina pasteurii* (Achal et al. 2009), with sodium acetate and a new cost-effective sequencing batch mode of injection were evaluated by Kakelar et al. (2016). A substantial cost saving (53.4%, compared with Al-Thawadi et al. 2012) was achieved with the UCS of 525 kPa and uniform $CaCO_3$ distribution even for poorly graded coarse sand using the proposed injection method, inducing an improved MICP cementation technology for practical enhancement.

Resisting soil liquefaction

Soil liquefication generally results from an applied stress such as shaking during an earthquake or other sudden change in stress condition and has led to significant failures (Burbank et al. 2011), posing great risks to the safety of geotechnical engineering (Stabnikov et al. 2015). Seismic-induced soil liquefication generally occurs in relatively loose sandy soils below the ground-water table. When seismic waves cyclically shear the soil, the porewater pressure of the soil increases and substantially decreases the shear strength of soil. Apart from some traditional technologies to prevent soil liquefication, including chemical cementation, densification, drainage and thermal stabilization (Mitchell et al. 1995; Chu et al. 2009), biological approaches have been taken into consideration because they are less toxic to the environment and less intrusive to property owners.

The saturation of the soil directly effects the pore water pressure under cyclic loading and consequentially decides the potential of soil liquefication. Therefore, desaturation is considered a key solution towards soil liquefication problems. Using microbially generated gas bubbles to desaturate sandy soils as a method to remediate liquefication was explored by researchers (Eseller-Bayat et al. 2012; Montoya et al. 2012; Simatupang and Okamura 2017). However, the desaturation state could only remain for a relatively long period under hydrostatic conditions (Yegian et al. 2007; He and Chu 2014). Relatively, the MICP process could obtain the cementation integrity, which promotes a change in the behavior of geomaterials from 'soil like' to 'rock like', with an increase in treatment level (DeJong et al. 2013). Particularly, the cohesion of soil increases as the calcium carbonate cements soil particles, thus preventing liquefication risk. The extra 21 kN/m^2 cohesion could be achieved for potentially liquefiable sand to meet the criterion of safety (Filet et al. 2012). In addition, the slight change of permeability suggests that MICP may provide a measure against liquefaction that does not disturb groundwater flow (Inagaki et al. 2011). O'Donnell et al. (2017a, 2017b) concluded the desaturation and MICP process as a two-stage process for the nondisruptive mitigation of liquefaction potential. In Stage One, short-term mitigation is provided by desaturation; in Stage Two, mitigation is provided by MICP. Hamdan et al. (2017) also proved the same mechanism that might be useful for mitigation of earthquake-induced liquefaction.

Tests have been carried out to prove the effectiveness of MICP for improving soil liquefication resistance, generally underscoring the dynamic response of treated soil (Table 1). Improvements in compressive strength of soil treated by MICP were observed carefully. In the centrifugal model tests subjected to ground motions consisting of sine waves with increasing amplitudes, the soil treated by MICP showed lower excess pore water pressure, higher acceleration response and lower residual deformation than untreated soil (Inagaki et al. 2011; Montoya et al. 2013). However, surface accelerations were also amplified at heavy levels of cementation. A compromise between improving liquefaction resistance and minimizing undesirable surface accelerations must be reached when designing the soil improvement level (Montoya et al. 2013). The use of bacteria solution and nutritive salt can be reasonably reduced, and solidified time can be shortened to 1 ~ 2 d because if the loose sand is strengthened to a "dense sand like" behavior, the solidified sand will not easily liquefy under an earthquake (MS8 seismic intensity) (Han et al. 2016). Apart from siliceous sand, calcareous sand is a biogenic material with natural advantages for the carbonate crystal-particle interface strength (Xiao et al. 2018, 2019a). For example, Khan et al. (2015, 2016) conducted some initial investigations on the coral sand using different bacteria and achieved unconfined compressive strengths in the range of 13 ~ 20 MPa. On the other hand, Sasaki and Kuwano (2016) found that siliceous sand with a 30% clay fraction showed no increase in liquefaction resistance following microbial precipitation of $CaCO_3$. This was because the void ratio of the mixture was much smaller than that of siliceous sand at a similar relative density, causing the clogging of the bacteria near the areas where bacteria were injected.

Biostimulation has also been proved to be an effective MICP approach in preventing liquefication in permeable soils with sufficient urease positive microorganisms (Burbank et al. 2011). In-situ field tests showed that the biostimulation approach of MICP could be applied in the field at a large scale. The CPT data showed liquefaction resistance of soil was increased significantly for some soils only with calcium carbonate precipitation of 3.5% or less (Burbank et al. 2011). Undrained cyclic triaxial shear showed the cyclic resistance ratio increased over two times for 2.1 ~ 2.6% calcite precipitation and 4 ~ 5 times for 3.8 ~ 7.4% calcite precipitation (Burbank et al. 2013).

Construction materials

Eco-friendly and durable building materials have always been a pursuit for green structural construction. Incorporating bacteria into the production of materials and external bio-treatment for existing materials are two main attempts towards improving the properties of construction materials using the MICP technology (Khaliq and Ehsan 2016; Choi et al. 2016a). In this part, popular applications of the MICP technology in construction materials are discussed. This technology could play different roles in building materials as categorized in following sections.

Improving cement/concrete mortar mechanical behavior

In the beginning, the trials of using the MICP technology for construction materials oriented introducing biomass into cement/concrete matrix to improve its properties (e.g., strength and durability). Adding microorganisms (e.g., *Shewanella*) alone was once proved effective to raise up the strength of cement matrix due to the fibrous organic material (mainly dead cells) produced in it (Ghosh et al. 2005). But it required a long period (28 d) for curing and a high concentration of bacteria but resulted in modest improvement. Remarkably, some successful trials relating to MICP treated concrete were conducted at the beginning of this century with the active bacteria and suitable substrates for carbonate precipitation incorporated into the cement/concrete mortar (De Muynck et al. 2010a). Ramachandran et al.

Table 1 Tests to prove the effectiveness of biological processes for sand liquefication resistance

Processes included	Testing methods	Bacteria/soils	Saturation obtained	Findings	References
MICP (Ureolysis)	Undrained Cyclic Triaxial Shear	*Sporosarcina pasteurii* / Calcareous sand	–	The effect of MICP treatment to improve the cyclic resistance of calcareous sands may be more effective than densification-based methods	Xiao et al. (2019a)
MICP (Ureolysis)	Undrained Cyclic Triaxial Shear	*Sporosarcina pasteurii* / Calcareous sand	–	The number of cycles to liquefaction increased with increasing cementation content in calcareous sand	Xiao et al. (2018)
Biogas desaturation	Centrifuge Model Testing	*Pseudomonas and Bacillus* / Ottawa sand	70%	45 cycles of loading with amplitude of 0.70 g tolerated,	Hall et al. (2018)
			90 ~ 95%	15 cycles of loading with amplitude of 0.35 g not tolerated	
Biogas desaturation	P-wave Velocity and Dialysis Bag Measurements	*Pseudomonas and Bacillus* / Ottawa sand	Near 95% (within 7 days)	Desaturation occurred quickly after the onset of denitrification (1 ~ 3 days)	O'Donnell et al. (2017a)
MICP (Denitrification)	Undrained Triaxial Compression Testing Drained Triaxial Compression Testing Cyclic Simple Shear	*Pseudomonas and Bacillus* / Ottawa sand	Near 95% (within 7 days)	Consistent improvements in static properties (shear strength, stiffness, and dilatant behavior), combined with the results of cyclic tests	O'Donnell et al. (2017b)
Biogas desaturation	Undrained Triaxial Compression and Extension Tests	*Acidovorax sp.* / Sand	95 ~ 88%	Undrained shear strength increased by more than two times	He and Chu (2014)
	Shaking Table Tests			The ground settlement generated under ground shaking with an acceleration of 1.5 m/s2 can be reduced by more than 90%	Chu et al. (2014)
Biogas desaturation	P-wave Velocity Measurement	*Paracoccus denitrificans* / Sands, silts, and clayey sands	–	When the fine content increases, sands reach a stable P-wave velocity faster than in clean sands	Rebata-Landa and Santamarina (2012)

(2001) investigated the use of MICP for the improvement of the compressive strength of Portland cement mortar cubes. Although the concentration of bacteria was relatively low (10^3 cell/cm^3), *Sporosarcina pasteurii* turned out to increase the compressive strength of mortar cubes from 55 ± 1 MPa to 65 ± 1 MPa. Comparatively, *P. aeruginosa* made little contribution to the strength of mortar cubes due to the alkaline environment and lack of oxygen.

Generally, the MICP process may have positive effects on enhancing the strength and durability of cement/concrete with bacteria incorporated (Al-Salloum et al. 2017). Moreover, it should be noted that one of the most dominating factors of the durability of cement/concrete is its porosity, which decides the permeability of various corrosive agents from the surroundings into the cement/concrete matrix (Aitcin 2003; Reinhardt and Jooss 2003; Aît-Mokhtar et al. 2013; Ma et al. 2014). MICP is an ideal process for occupying these voids within a maturing cement/concrete matrix (De Muynck et al. 2008a, 2008b). With active bacteria and suitable substrates for carbonate precipitation added into the mortar, the bacteria can move into the voids and produce carbonate, which efficiently plugs the pores or inhibits the pore connectivity (Chahal and Siddique 2013; Siddique et al. 2016a, b). In this way, the bacteria were observed to increase the resistance toward alkali, sulfate, freeze thaw attack and drying shrinkage of the cement/concrete (Anbu et al. 2016). Also, this positive impact increased with the concentration of bacteria (Ramakrishnan et al. 2001). Similar positive results have been reported in many other researches centering the strength and durability of MICP cement/concrete mortar (Table 2). However, one challenge for incorporating bacteria into cement/concrete is that the increase in biomass, particularly dead cells, could conversely decreased the strength since the disintegration of the organic matter makes the matrix more porous (Ramachandran et al. 2001). Another problem is the loss of bacteria added in the cement/concrete mortar due to the continuously decreasing pore size and high pH of the matrix, which is earnestly discussed in following parts.

Table 2 Previous studies on incorporating bacteria for improving cement/concrete mortar

Bacteria	Improvement	Supplement	References
Bacillus subtilis	Compressive strength (+25.8%) Splitting tensile (+22.7%) Flexural strength (+22%)	After 60 cycles of freezing and thawing	Suliman et al. (2018)
Sporosarcina pasteurii	Compressive strength (+36.6%)	Substrate solution significant influences the strength	Al-Salloum et al. (2016)
Enterobacter	Compressive strength (+29%) Tensile strength (+47%)	Various calcium sources compared	Senthilkumar et al. (2015)
Enterobacter	Compressive strength (+44%)	Calcite, vaterite and aragonite identified	Senthilkumar et al. (2014)
Bacillus subtilis	Compressive strength (+15%)	Bacterial cell walls (not dead cells) accelerated carbonation of Ca^{2+}	Pei et al. (2013)
Bacillus Subtills	Compressive strength (+19.26%) after 28 days	17.3% increase in 3 days 15.57% in 7 days	Vamped et al. (2011)
Salini coccus sp.	Compressive strength (+2.91%) after 28 days	16.01% increase in 3 days 3.44% in 7 days	Vamped et al. (2011)
Arthrobacter crystallopoietes	Compressive strength (+8.9%) after 28 days	13.6% decrease in 7 days	Park et al. (2010)

Table 3 Concrete mortar with different compositions improved by MICP

Concrete addictive	Bacteria	Effects	References
Cement baghouse filter dust	*Bacillus aerius*	Compressive strength increased, permeability reduced	Siddique et al. (2016a)
Rice husk ash	*Bacillus aerius*	Compressive strength increased, water absorption, porosity, and permeability reduced	Siddique et al. (2016b)
Fly ash	*Acinetobacterjohnsonii*	Compressive strength increased, capillary water uptake reduced	Li et al. (2015)
Cement kiln dust mortar	*Bacillus sp.*	Compressive strength increased, water consistency increased	Siddique and Rajor (2014)
Fly ash and silica fume	*Sporosarcina pasteurii*	Compressive strength increased, porosity and permeability reduced	Chahal and Siddique (2013)
Fly ash	*Sporosarcina pasteurii*	Compressive strength increased, permeability reduced	Chahal et al. (2012)

Producing composite concrete/bio-bricks

Apart from common cement/concrete mortar, some researchers tried to analyze the effects of utilizing MICP for concrete with different compositions like fly ash, silica fume, cement kiln dust, baghouse filter dust, rice husk ash and blast-furnace slag (Table 3). Here, the economic and ecological advantages featured by MICP are reckoned on to a larger extent. And this roadmap has been further developed in producing innovative bio-bricks. Conventionally, producing a unit clay brick releases 0.41 kg of CO_2 and utilizes 2.0 kWh of energy (Zhang 2013). Thus, a more sustainable approach for brick manufacturing which releases less CO_2 and utilizes less energy has been considered into practice. Recently, a natural, bio-mediated process for the manufacturing of bio-bricks has been seen as a novel solution for those considerations of sustainability (Fig. 7) (Bernardi 2012).

The cooperation between researchers and enterprises has promoted the development of bio-bricks. MICP could be used to manufacture bio-bricks, which provides a method for producing construction material utilizing loose pieces of aggregate, enzyme producing bacteria, urea and calcium ions (Dosier 2011). The process eliminates the need to burn fuel to heat a kiln to 2000 °F, as is commonly required in clay-brick production, thus cutting down immensely on the amount of CO_2 released into the atmosphere during brick production. Through the design of mold and solidification model, the special customization of the appearance of mineralized cement could be achieved. Specific properties, such as hardness, brittleness, water-resistance, and freeze–thaw reactions are also available to provide a bio-brick structural and performance properties similar to a standard clay brick (Larson 2010). However, synthetic urea is manufactured using the Haber Bosch process still at high pressures (150 ~ 300 atm) and high temperatures (400 ~ 500 °C) and thus the process is highly energy-intensive (Chesworth 2007). Some researchers have used pig urine as an alternative source of urea for MICP (Chen et al. 2018). Remarkably, Randall and his group investigated using MICP and the remnants of human urine after being recovered for fertilizer production to manufacture bio-bricks (Randall and Naidoo 2018). The highest compressive strength of a bio-brick they made was 2.7 MPa (Lambert and Randall 2019). Cheng et al. (2020) utilized MICP to produce bio-bricks under 50% treatment saturation condition. The produced bio-bricks under partially saturated condition gave compressive strength of 9 MPa, which is twice the strength obtained from the fully saturation condition approach. Various mechanical properties including the water absorption (about 10%), salt attack reaction (mass loss about 0.5 g) also demonstrated that the produced bio-bricks were suitable for use as a construction material (Cheng et al. 2020).

The conception of 'Reducing', 'Reusing' and 'Recycling' is considered as an important part of sustainable development. Fitting into this background, bio-bricks produced by brick aggregate and recycled concrete aggregate have also been pondered over earnestly (Dhami et al. 2013). Rautray et al. (2019) generated bio-bricks from common agro-waste, which has a tremendously better net carbon footprint than standard building materials and are very cheap and simple in production. They may have huge application potential in less-load bearing wall construction, sounds reduction and insulation, particularly in the low-cost sector. Grabiec et al. (2012) presented a surface modification of recycled aggregate using MICP method involving *Sporosarcina pasteurii* bacteria, calcium chloride (for carbonate precipitation) and culture medium containing beef extract, peptone and urea (for cultivating organisms). Plus, by-product from dairy industry, which is widely considered ecologically dangerous, was found to be effective as a cultural medium. Manzur et al. (2019) studied the performance enhancement of brick aggregate by MICP, finding a good way to ensure sustainable construction. It was found that 48 h incubation for bacteria culture was more effective than 24 h incubation. The longer incubation resulted in almost twofold reduction in aggregate absorption test. Compressive Strength, Rapid Migration Test (RMT) and Rapid Chloride Penetration Test (RCPT) of brick aggregate concrete resulting from 48 h incubation showed 14%, 43% and 27% improvement over untreated brick concrete, respectively (Manzur et al. 2019).

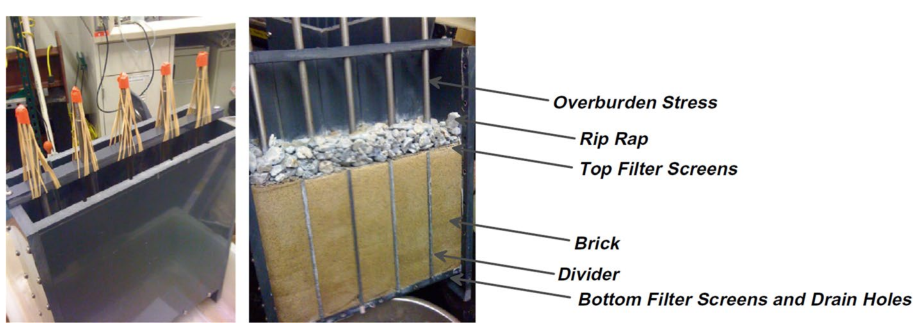


Fig. 7 Image of assembled bio-brick mold (left image with one side removed for display purposes) (Bernardi et al. 2014)

Remediating cracks

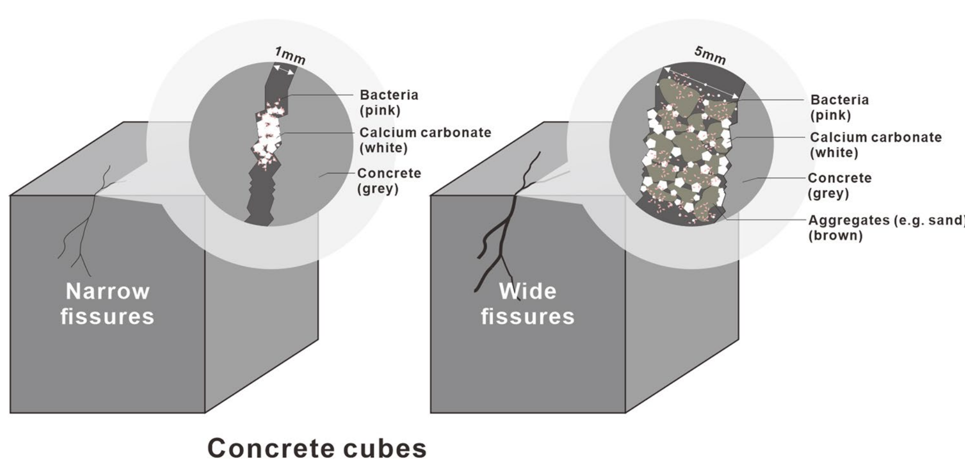
Another approach to construction material improvement via MICP is widely known as external treatment, which involves treating existing construction materials externally, for remediation. Generally, cracks may form in concrete structures due to aging and/or freeze thaw cycles which lead to permeability for corrosive agent intrusion (Bang et al. 2010; Wiktor and Jonkers 2011). If the cracks are left untreated, they tend to expand further and lead to costly repair as a result. The use of an external treatment to help heal cracks in concrete via MICP seems a promising approach since traditional sealants may degrade over time or are environmentally toxic; whereas calcium carbonate is a more durable and benign crack sealant (Siddique and Chahal 2011).

In the beginning of this century, many researchers started to investigate this microbiological way for crack remediation in concrete structures (Ramachandran et al. 2001; Bang et al. 2001). Bang and his research team referred to this concept as ‘microbially-enhanced crack remediation’, which means healing fissures with prepared bacteria solution and substrate for carbonate precipitation (Bang et al. 2001). In fact, there have been multiple considerations for realizing the MICP reaction in the cracks of concrete (van Tittelboom et al. 2010; Ducasse-Lapeyrusse et al. 2015).

The external treatment process involves allowing bacteria solution and substrate penetrate into the crack by capillary action simultaneously, and carbonate would be deposited at the opposite surfaces of the crack till the gap is filled completely through bacterial activity (Al-Salloum et al. 2017). De Muynck and his group prepared concrete mortar cubes and immersed them respectively in bacterial culture medium, nutrient and calcium source (calcium chloride/calcium acetate) for MICP treatment (De Muynck et al. 2008a). They recorded improvement in gas, water and chloride permeability as well as tolerance to freezing-thaw cycles due to calcite deposition (De Muynck et al. 2008b; De Belie and De Muynck 2008). Similar results were observed by treating cement-based building materials with MICP (Amidi and Wang 2015; Qian et al. 2009). But this method is only effective for remediating narrow fissures (Fig. 8). For wider fissures (about 3 mm in width), Ramakrishnan et al. (2001) applied *Bacillus Pasteurii*, nutrient substrate, calcium source and sand (as aggregate) to fill cracks in cement mortar. The strength and stiffness of the cement mortar were both reported to increase gradually as the curing progressed. Jongvivatsakul et al. (2019) externally applied *Bacillus sphaericus* and urea solutions daily to the cracked mortar specimens. After twenty days of treatment, the MICP-treated sample showed 43% higher compressive strength than that of cracked sample and it is comparable in terms of water tightness to control mortar made without artificial cracks. Shallower fissures got better remediation than deeper ones since the aerobic environment was better for the growth of bacteria. Moreover, the high pH value (11 ~ 12) of the cement-based material hinders the activity of bacteria in cracks, especially for those deep ones, which poses a challenge to crack remediation through MICP.

It is also reasonable to separate the bacteria solution and substrate for a two-phase treatment. For instance, the method of introducing bacteria in advance into cracks and applying calcium source for remediating cracks when necessary has attracted interest. De Belie and De Muynck (2008) filled cracks with a mixture of bacteria and silica sol (for protecting bacteria) and then cured the specimens in a solution containing urea and calcium chloride. They found the permeability of the specimens was reduced to a lower degree compared with traditional crack-remediating technologies. Achal et al. (2013a) used the same method for concrete mortar but replaced silica col with sand. They reached an improvement of 37% for the compressive strength of specimens. Abo-El-Enein et al. (2012) also found the remediated specimens only showed a lowering in strength of 10% than the control cement mortar specimens, whereas the untreated ones showed a lowering of 43%. Choi et al. (2017b) developed a cyclic method of soaking the cracked mortar samples

Fig. 8 Schematic drawing of healing process of concrete cubes through the MICP treatment (left: the case of narrow fissures; right: the case of wide fissures)



in the bacterium solution firstly and in the urea-calcium solution secondly. The results indicated that the MICP technology greatly reduced water permeability of the samples. The MICP-repaired samples had a splitting tensile strength ranging from 32 ~ 386 kPa after twenty-one cycles of MICP solution treatment. A relationship between the tensile strength and amount of calcium carbonate precipitated was observed for samples, which indicated that tensile strength increased with the amount of calcium carbonate precipitated on the crack surfaces (Choi et al. 2017b). Plus, the method of incorporating calcium source alone in cement/concrete mortar and applying bacterial culture after the appearing of cracks also seems practical because it would circumvent the difficulty of retaining bacteria in vegetative or sporulated form for a long time (Al-Salloum et al. 2017). But elementary experiments still need to be carried out about this approach.

Natural building materials like stones, have also been taken into account while using the MICP technology for remediation (Minto et al. 2016; Wu et al. 2020). Dick et al. (2006) found *Bacillus sphaericus* isolated from calcareous sludge effective at precipitating calcium carbonate on limestone cubes. They soaked the cracked mortar samples in the bacterium solution firstly and in the urea-calcium solution secondly. The bacteria with a negative zeta(ζ)-potential on surface would efficiently colonize positive zeta (ζ)-potential limestone and produce homogeneous and coherent calcium carbonate coating. De Muynck et al. (2010b) concluded that the resistance of the limestone to water absorption improved with higher urea and calcium concentrations and repeated treatment. But the benefits of higher urea and calcium chloride concentration should reach a compromise with the detrimental impacts such as unwanted ammonium by-product formation or stone discoloration. Also, it was concluded that the successful bacterial penetration into larger pores led to more calcium carbonate deposition in limestones with higher porosity (De Muynck et al. 2011). Cheng and his group made field trials in the Potala Palace, Tibet through bio-grouting to test the applicability of the MICP technology for remediating deteriorated masonry structures (Yang and Cheng 2013). Visual inspection showed that bio-mediated sandstone was the only material survived the harsh environment conditions (e.g., huge temperature differences between day and night) without visual cracks compared with those sandstones mediated by lime or cement. The high-strength microbial mortar they developed had a larger pore size, higher splitting tensile strength and a higher capability. Compared with traditional mixed mortar, this high-strength microbial mortar withstood cyclic loading and was particularly suitable for strengthening ancient masonry structures that have been damaged by earthquakes (Yang et al. 2011). Other researchers also proved the advantages of the MICP technology on remediating ornamental stone, conserving stone culture heritage and regenerating historic patrimony

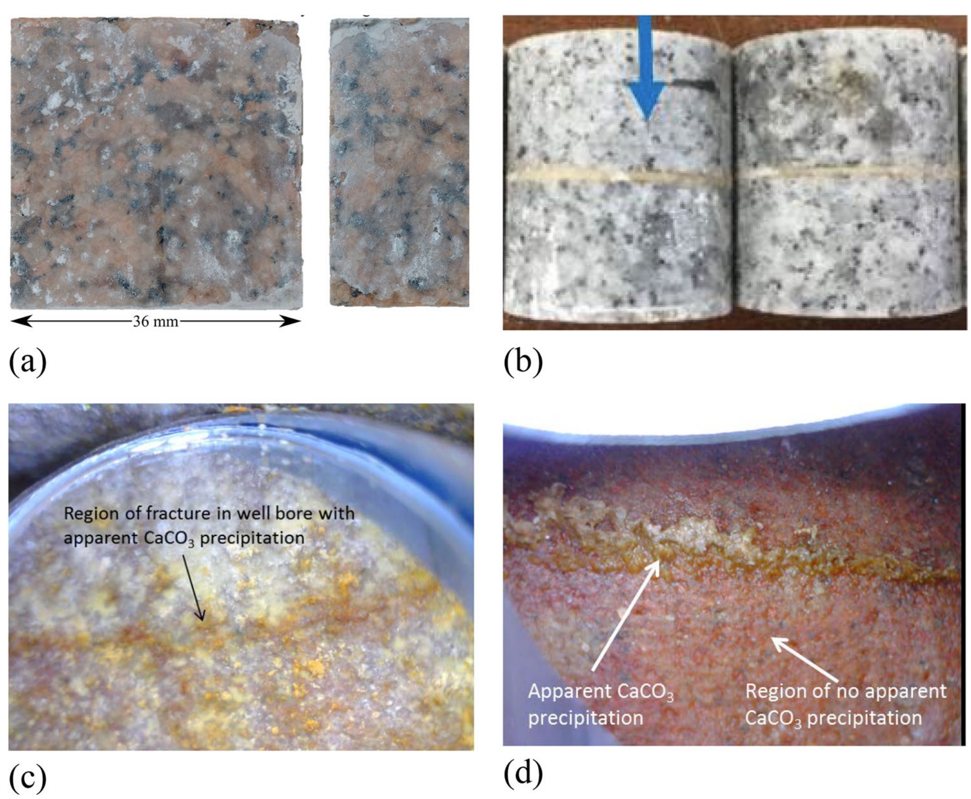


Fig. 9 MICP repair of fractures: (**a**) Calcium carbonate deposited on granite fracture surfaces; (Tobler et al. 2018); (**b**) Horizontal fractures after MICP repair (Wu et al. 2020); (**c**) Arrows point to the primary horizontal sandstone fracture which was strengthened with $CaCO_3$ precipitation; (**d**) Arrows show regions of apparent $CaCO_3$ and an area where no apparent $CaCO_3$ is observed (Phillips et al. 2013)

(Fig. 9) (Le Metayer-Levrel et al. 1999; Rodriguez-Navarro et al. 2003; Fernandes 2006; Liu et al. 2018, 2020c).

A step forward: self-healing building materials

Eco-friendly building materials are being constantly invented. Among them, smart and reliable materials are embedded with self-resilience to future problems such as damage or aging. Since the applicability of utilizing bacteria as the self-healing agent for remediating cracks in concrete was autogenously investigated (Jonkers and Schlangen 2007; Jonkers et al. 2010), it has been a popular research focus on the development of sustainable concrete. Autogenous remediation of concrete is the process of healing of cracks in cementitious matrix naturally, without the aid of any additive or any external intervention (Luo et al. 2015; Lors et al. 2017). Minimal externally triggers are needed for the commencement of remediation. And suitable bacteria should be chosen to survive concrete incorporation for prolonged periods of time (Fig. 10). The heat and alkali resistant bacterial spores, which are able to endure extreme mechanical and chemical stress, and nutrients can be mixed into the concrete mortar. Once the external water and oxygen enter into the cracks, the spore recovery and cracks repair through bacterial mineralization are initiated (Xu and Yao 2014; Tziviloglou et al. 2016) (Fig. 11). For example, *Lysinibacillus boronitolerans* isolated from the rhizosphere of *Miscanthus sacchariflorus* has triggered attention because of its heat and alkali tolerance as well as high efficiency of calcium ion consumption (Lee et al. 2017). The increased pH in the urea-minus condition during the growth of the *Lysinibacillus boronitolerans* strain promoted calcium carbonate formation (Lee and Park 2019), which made it a suitable candidate for self-healing concrete (Ryu et al. 2020).

Nevertheless, the bacteria added in the cement/concrete mortar in advance may still suffer from great loss due to the continuously decreasing pore size and high pH of the matrix within the progress of curing (Wang et al. 2014; Pacheco-Torgal and Labrincha 2014). To overcome these obstacles, Bang et al. (2001) employed polyurethane foam to immobilize the bacteria early in this century. van Tittelboom et al. (2010) immobilized the bacteria in silica gel. Wang et al. (2012a) also suggested diatomaceous earth for protecting bacteria from the high pH environment. The bacteria immobilized by diatomaceous earth have a higher ureolytic activity (12 ~ 17 g/L urea decomposed in 3 d) than unimmobilized bacteria (< 1 g/L urea decomposed in 3 d) in the concrete mortar and the optimal concentration

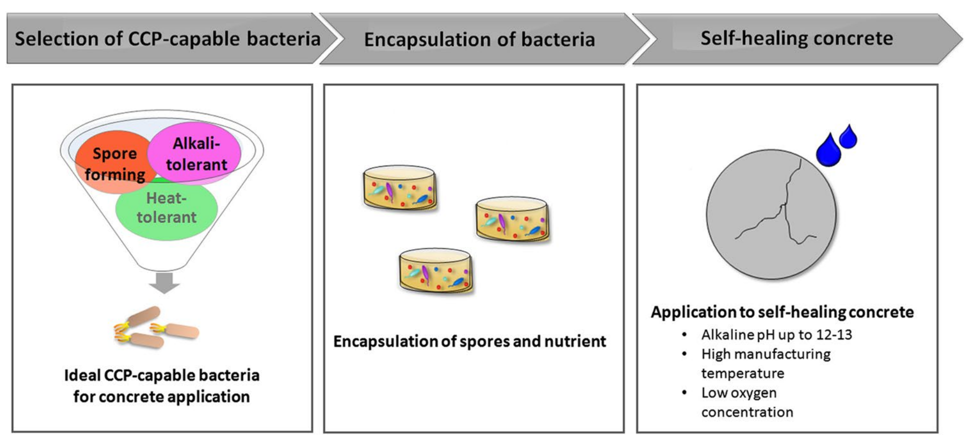


Fig. 10 Conception of using ideal bacteria to create self-healing concrete (Lee and Park 2018)

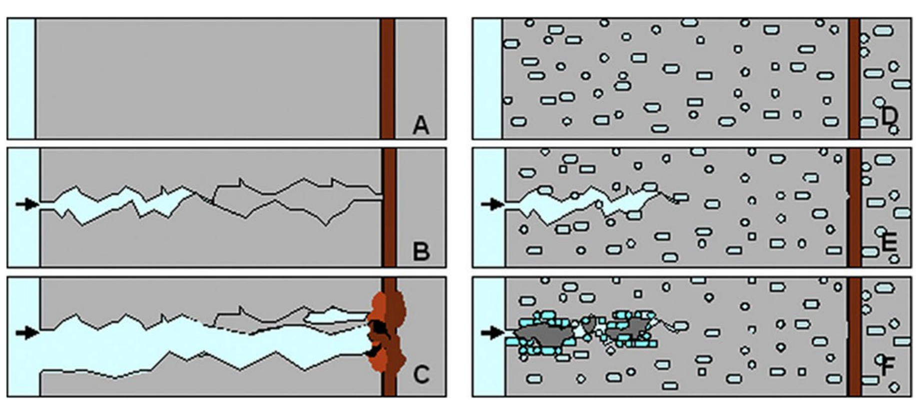


Fig. 11 Schematic drawing of conventional concrete (**A–C**) and bacteria-based self-healing concrete (**D–F**); Crack ingress chemicals degrade the material matrix and accelerate corrosion of the reinforcement (**A–C**); Incorporated bacteria-based healing agent activated by ingress water seals and prevents further cracking (**D–F**) (De Muynck et al. 2010a)

of diatomaceous earth for immobilization was 60%. Wang et al. (2012b) compared two different techniques (silica gel and polyurethane) for immobilizing bacteria in the concrete. It turned out that silica gel-immobilized bacteria showed a higher activity than polyurethane-immobilized bacteria, and more $CaCO_3$ was precipitated in silica gel (25% by mass) compared with polyurethane (11% by mass), which was also proved by thermogravimetric analysis. However, specimens treated with polyurethane-immobilized bacteria had a lower water permeability coefficient ($10^{-10} \sim 10^{-11}$ m/s) compared with those treated with silica gel-immobilized bacteria ($10^{-7} \sim 10^{-9}$ m/s). Bundur et al. (2017) used an ammonium salt-based air-entraining admixture (AEA) to improve the survival of incorporated *Sporosarcina pasteurii* cells in cement-based mortar. Xu and Wang (2018) developed a protective carrier for the bacteria by using calcium sulphoaluminate cement, which is a type of low alkali, fast hardening cementitious material. Expanded clay was also proved useful to combine nutrients and bacteria in the pores of clay to isolate them from surface of the concrete, protecting them from stress (Han et al. 2019).

As mentioned above, it is reasonable to prevent the loss of microorganisms through immobilization, which means replacing the aggregate material partially with homogeneous microorganism carriers like silica gel, polyurethane, expanded clay, etc. For the same purpose, researchers also suggested an encapsulation of bacteria before the addition to the concrete mortar, namely compressing bacteria and nutrients directly into a capsule (Jonkers and Schlangen 2007; De Koster et al. 2015), further ensuring the spore recovery and crack repair operation (Lucas et al. 2018). Aimi et al. (2016) encapsulated *Geobacillus stearothermophilus* with alginate as a new smart material for self-healing concrete. Seifan et al. (2018) proved the addition of immobilized *Bacillus* species with iron oxide nanoparticles (IONs) in concrete matrix had a self-healing function and increasing of the compressive strength was observed. Alazhari et al. (2018) used coated expanded perlite to immobilize bacterial spores and encapsulate nutrients as two separate components for self-healing concrete. It was found that optimistic healing could be achieved when coated expanded perlite containing self-healing agents was used as a 20% replacement of fine aggregate and a suitable ratio of spores to calcium acetate was provided. Pungrasmi et al. (2019) encapsulated spores of *Bacillus sphaericus* with sodium alginate so as to protect the bacterial spores during the concrete mixing and hardening period. It was found that freeze drying had a high potential as a microencapsulation technique for application to self-healing concrete technology compared with extrusion and spray drying (Fig. 12).

Ureolysis is undoubtedly a suitable and reliable process for producing self-healing concrete but not necessarily the ultimate plan due to problems like harmful byproduct. For example, Erşan et al. (2016) presented the nitrate reduction as an alternative microbial self-healing strategy and used nitrate reducing bacteria with

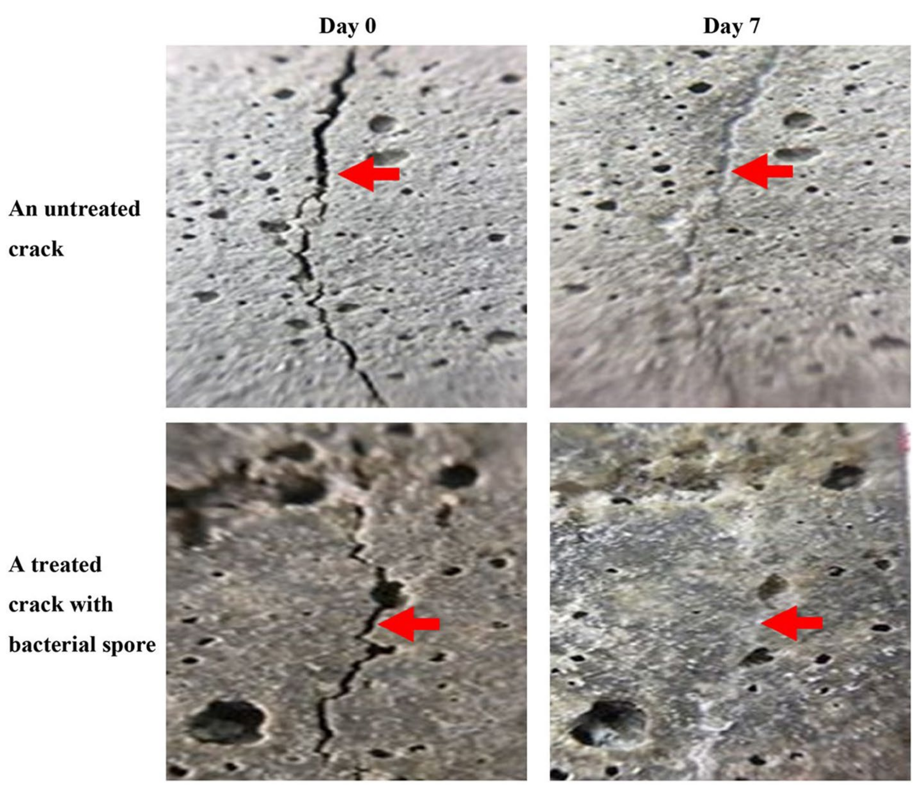


Fig. 12 Crack-healing activity in mortar by sodium alginate microencapsulated bacterial spores formed by freeze drying (Pungrasmi et al. 2019)

two different porous protective carriers. The highest crack width healed by the bacteria was 370 ± 20 μm in 28 d and 480 ± 16 μm in 56 d. Moreover, possible negative effects of the produced ammonia on the reinforcement corrosion and degradation of the concrete matrix (when oxidized by bacteria to yield nitric acid) could be avoided through this method (De Muynck et al. 2010a). While most researches on microbial crack self-healing concrete use a single type of microorganism and the experiments are carried out under the environment suitable for the survival of microorganism, the working environment of concrete mortar is often complex and changeable (Khaliq and Ehsan 2016). Thus, a single type of microorganism is less likely to resist. On the contrary, a microbial consortia composed of various microorganisms can perform more complex tasks, and has better performance in resisting environmental fluctuation of self-healing materials compared with single microorganism (Brenner et al. 2008; Da Silva et al. 2015b, a; Erşan et al. 2015 Zhang et al. 2017). Zhang et al. (2019) compared the healing efficiency of different cultures, i.e., two microbial consortia under anaerobic (MC-Aa) and anoxic (MC-Ao) conditions and non-ureolytic pure-culture bacteria (*Bacillus cohnii*). The MC-Ao agent exhibited the maximum values of completely healed crack widths (1.22 mm) after 28 d of healing, which was larger than the values of 0.79 mm and 0.73 mm for *B. cohnii* and MC-Aa, respectively. It was confirmed that the biominerals induced by MC-Aa and *B. cohnii* are calcite, while those of MC-Ao were 82% aragonite and 18% calcite, showing an advantage of aragonite in self-healing of cracks.

Obviously, the cost involved is one of the challenges for applying the MICP technology on concrete self-remediation, which counts for industrial application. Thus, the economic feasibility has been analyzed in many literatures (Palin et al. 2015; Silva et al. 2015b, a; Wiktor and Jonkers 2016). To reduce the cost, Achal et al. (2009) once used the industrial effluent of the dairy industry, lactose mother liquor (LML) as growth medium and the bacteria growth, urease production and compressive strength of mortar showed insignificant difference compared with standard media like nutrient media and yeast extract media. Ryu et al. (2020) confirmed the feasibility of malt powder, rice bran and corn syrup to enhance the growth of *L. boronitolerans*, instead of using synthetic microbial media like yeast extract. In addition, economic evaluation verified that the microbial consortia resulted in a 61% decrease in production costs compared to pure cultures (Zhang et al. 2019). These studies above seem worthwhile because of their ecological, technical and financial reasons since the production of standard media and pure microbial cultures relies on high-emission, high-tech and high-cost industries. Nevertheless, until now, the effects of the presence of the microorganisms or the microbially induced carbonates on the microstructure still need to be further elucidated.

Consideration has been given to self-healing of biocemented materials (e.g., sand) in recent studies by Spencer and Sass (2019) and Botusharova et al. (2020). This is also considered worthwhile, especially when MICP is combined with the effects of additives such as natural fibers (Spencer et al. 2020).

Hydraulic engineering

Leakage of useful or harmful liquids and common hydraulic erosion pose obvious engineering issues in the realm of hydraulic engineering. Internal erosion and surface soil erosion also become a serious concern for hydraulic structures and geological bodies. In this part, these two typical applications of the MICP technology in hydraulic engineering are envisioned and discussed for the sake of polishing up the hydraulic properties of geomaterials.

Mitigating leakage

Leakages in hydraulic-engineering water retaining constructions or in natural impervious layers are major problems in constructional and environmental applications. In China, more than half the water resources for agricultural use are wasted in the process of transportation due to lack of leakage control measures (Gao et al. 2019). Traditional techniques for sealing these leakages have many disadvantages as they are expensive and environmental unfriendly. As a novel method, biosealing is suitable for in-situ clogging of leakages in subsurface constructions and natural layers (Blauw et al. 2009). Thus, attempts to use biosealing to diminish the hydraulic conductivity of the dams and dikes and to reduce infiltration from the ponds and leakage in construction sites or landfills have never been suspended.

Biosealing technology mainly uses metabolites of microbial action and products of biochemical reactions as pore filling materials to reduce permeability. At present, there are two main ways of microbial sealing: one is to use MICP to form biofilms (El Mountassir et al. 2018). Biofilms form when microorganisms adhere to a surface and excrete extracellular polymeric substances (EPSs) as part of their metabolism (Thullner and Baveye 2008; Bai et al. 2017). It has been verified that the growth of biofilms can reduce hydraulic conductivity (Baveye et al. 1998). However, it should be noted that due to the degradability, thermal sensitivity and low mechanical resistance to pressure drop, the durability of their clogging action is not guaranteed. On the contrary, the inorganic biocementation has better stability and mechanical properties, so MICP is considered to have more potential, especially when introducing the urease-producing bacteria like *Bacillus pasteurii* (Bachmeier et al. 2002; Hammes et al. 2002). Due to this enzymatic reaction, pH is increased and hydrocarbonate is produced. Then the precipitation of calcium carbonate can clog the pores and bind soil particles (Yang et al. 2019).

The applicability of MICP in leakage mitigation should be estimated based on its on-site testing results and costs. Stabnikov et al. (2011) examined the feasibility of using MICP to form an impermeable crust on top of a sand layer. A mixture of calcium salt, urea, and bacterial suspension was used. Applying 0.6 g of Ca per cm^2 of sand surface, the permeability of the sand could be reduced from 10^{-4} m/s to $1.6 \cdot 10^{-7}$ m/s (or 14 mm/d) due to formation of the crust on sand surface. The formation of a water-impermeable crust layer on sand surface could be useful for the construction of aquaculture ponds in sand and sealing of the channels and reservoirs in sandy soil. Chu et al. (2013) used the MICP process to form a low permeability layer in sand for the construction of a water pond model in the laboratory. The test results indicated that the permeability of sand was reduced from the order of 10^{-4} m/s to 10^{-7} m/s when an average 2.1 kg of calcium (Ca) per m^2 of sand surface was precipitated. Stabnikov et al. (2016) showed MICP treatments can decrease hydraulic conductivity of sand from 10^{-4} to 10^{-8} m/s. The cost of this sealing, especially when the local sources of calcium chloride brain or low-grade iron (hydr)oxides of iron ore are applied, could be several times lower than any other known methods of the sand sealing. MICP could be used in aquaculture practice for the construction of fish, prawns, or algae ponds in sand of the arid deserts. Gao et al. (2019) used the MICP-based soil improvement method to control water leakage in irrigation channels and reservoirs built on sandy soil grounds (Fig. 13). Using this method, a low-permeable hard crust can be formed at the soil surfaces. Yang et al. (2019) proposed a new method for seepage control in sand using bioslurry, which could permeate through sand or deposit on top of a sand layer. The water barrier layer formed was much less affected by wet and dry or temperature change cycles than compacted clay liners. It also allowed cracks in the water barrier layer to be repaired if required.

Apart from preserving water resources, subsurface fluid leakage is also an important environmental risk in unconventional oil and gas exploitation, CO_2 geological storage and nuclear waste disposal (Phillips et al. 2016; El Mountassir et al. 2018). The MICP process is highly effective for decreasing flow channels of media (e.g., soils and stones), especially in the presence of fractures which appears to create new nucleation sites for capturing bacteria clusters (Phillips et al. 2016; Wu et al. 2019a, b). This mechanism of selective plugging is prospective in improving storage security of geologically stored CO_2 or sealing fractures caused by hydraulic fracturing (Phillips 2013). MICP technologies use low viscosity fluids to penetrate small aperture pores that may not be reachable by traditional cement-based sealing technologies (Phillips et al. 2013; Bucci et al. 2016). Cunningham et al. (2014) did a field experiment in a hydraulically fractured sandstone formation at a Walker County, Alabama well. The injectivity was greatly reduced, indicating that the fractured formation was plugged after MICP treatment. Phillips et al. (2018) demonstrated MICP treatment of compromised wellbore cement at a depth interval of 310.0 ~ 310.57 m (1017 ~ 1019 feet) below ground surface using conventional oil field subsurface fluid delivery technologies. The flow rate was decreased while maintaining surface pumping pressure below a maximum pressure of 81.6 bar (1200 psi), revealing the lifted wellbore cement integrity (Fig. 14a). Kirkland et al. (2020) characterized a failed waterflood injection well and provided proof of principle that MICP can reduce permeability in the presence of oil using conventional oilfield fluid delivery methods. *Sporosarcina pasteurii* cultures and urea-calcium media were delivered 2290 ft (698 m) below ground surface using a 3.75 gal (14.2 L) slickline dump bailer to promote mineralization in the undesired flow paths. By Day Six and after twenty-five inoculum and forty-nine calcium media injections, the injectivity (gpm/psi) had decreased by approximately 70% (Fig. 14b). Song and Elsworth (2020) envisioned using MICP instead of EPSs for plugging

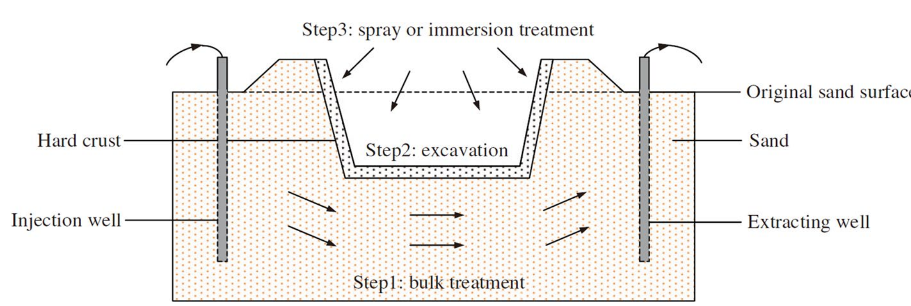


Fig. 13 Schematic diagram of irrigation channels and water reservoirs construction in sandy soil ground by MICP methods (Gao et al. 2019)

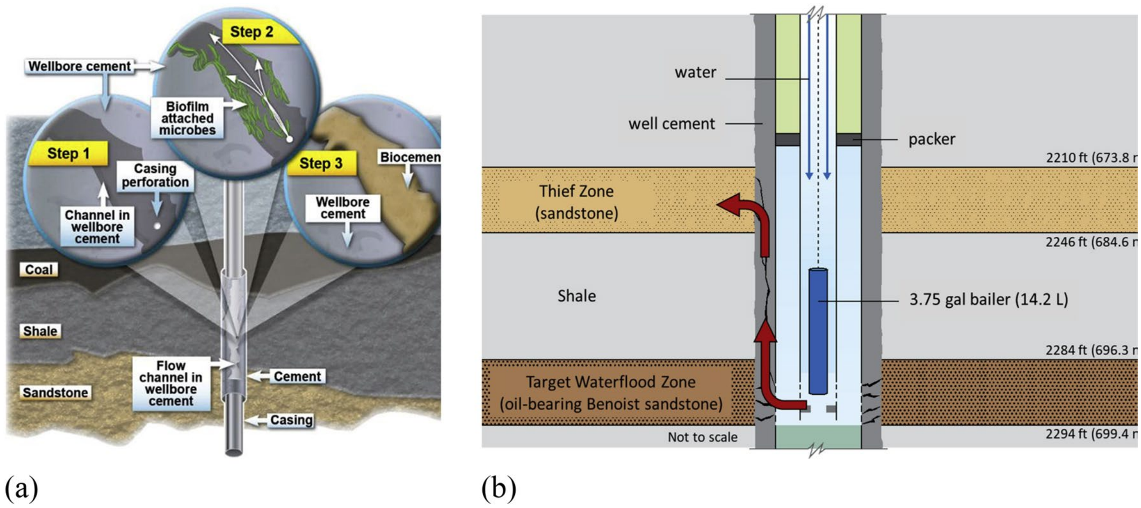


Fig. 14 (**a**) Biomineralization promoting fluids are injected into the channel where a mineral seal forms to limit further fluid injection (Phillips et al. 2018) (**b**) Conceptual model: microbial cultures and urea-calcium media were delivered to reduce flow through the undesired flow paths (Kirkland et al. 2020)

high-permeability zones within oil reservoirs to enhance oil recovery. After eight cycles of microbial treatment, the permeability for the artificial cores representing large, intermediate, and small pore size maximally dropped to 47%, 32%, and 16% of individual initial permeabilities, showing a higher efficiency in plugging pores compared with EPSs. This MICP technology has as huge advantage because the leak location does not need to be known precisely and biosealing will take place specifically at the location of the leak.

Controlling erosion

Piping and internal erosion are common problems for hydraulic engineering. For example, as one of the most commonly encountered hydraulic infrastructures worldwide, earth embankment dams have been troubled by the piping problem for many years. The earth core is often constructed using locally available soils, including clay, sand-clay mixtures, sand-silt mixtures, and in some cases, with gravel (Jiang et al. 2014). It is reported that internal-erosion-induced collapse is the third most important mode for earth dam failure after overtopping and external erosion, and it accounts for 14.3% of all dam failures (Danka and Zhang 2015). When segregation of fill materials and formation of transverse cracks in the earth cores occur, the fines will be dislodged and transported along preferential flow paths to downstream unprotected exits. Gradually, this process works its way backward to the upstream side of the dam until a through-piping forms. Internal erosion within earth-filled dams can be prevented by zoning of the dam (Foster et al. 2000), construction of filters (USBR 2011), chemical stabilization (Indraratna et al. 2013), and other embankment design and foundation treatment measures (Fell 2005). Actually, the target of the treatment is not to improve the strength of the treated soil, but to reduce erodibility while keeping the permeability of the treated soil almost constant. In this sense, MICP is an alternative solution for internal erosion problems and shows the potential of MICP for full-scale application. Applying MICP to mitigate hydraulic erosion, especially internal erosion, for different compositions of soil has been investigated by researchers (Table 4).

Table 4 Practice on soil internal erosion control via MICP

Bacteria	Soil types	Applications	References
Sporosarcina pasteurii	Gravel-sand mixtures	Internal erosion resistance improvement	Juang et al. (2019a) Jiang and Soga (2017)
Sporosarcina pasteurii	Sand-clay mixtures	Internal erosion resistance improvement	Jiang et al. (2017)
Bacillus sphaericus	Dispersive soil	Stabilization of dispersive soils	Moravej et al. (2017)
B. megaterium	Sand	Sand production control during hydrate gas exploitation	Jiang et al. (2016)

Apart from internal erosion, surface soil erosion also poses a serious concern with rapid industrialization and urbanization development. Against the background of climate change and frequent extreme weather, the surface erosion problem is turning worse. Surface soil erosion mainly consists of three processes: particle detachment, runoff transport, and deposition (Fang et al. 2015). Among them, soil particle detachment is predominantly initiated by rainfall impact (Assouline and Ben-Hur 2006). When raindrop kinetics energy overcomes soil shear strength, soil particles are mobilized and dislodged (Fattet et al. 2011). Runoff transport and deposition are dependent on sheet flow conditions (runoff rate, flow depth, and flow velocity) and slope surface conditions (surface roughness, slope length, and steepness) (Kinnell 2005). The most popular sustainable slope erosion control method is vegetation establishment (Norris et al. 2008), but it usually takes a long time to achieve its full functionality. The viability of MICP in surface erosion control has been recently analyzed (Salifu et al. 2016; Jiang et al. 2019; Liu et al. 2020a). It also calls for attention that the MICP methodology for surficial soil treatment to mitigate water-induced erosion can be positively coupled. For instance, the cementation solution for MICP can be prepared in a water solution of polyvinyl alcohol (PVA) instead of water alone, which leads to a uniform soil crust in the surficial region and reduces the erodibility of sands (Wang et al. 2018a).

The MICP technology is also envisaged to form an anti-erosion layer on the surfaces of buildings and constructions as protection, especially those with long history. For example, Liu et al. (2020b) investigated the effectiveness of the anti-erosion of an MICP coating on the surfaces of ancient clay roof tiles. MICP was found to significantly improve the water resistance of tiles by changing the microstructure of the surface. The MICP protection layer provides considerable durability with little negative impact on the air permeability and color of the sample. Plus, MICP-based coastal erosion control is a type of soft structural protection which has gained strong interest in recent years (Imran et al. 2019; Shahin et al. 2020; Liu et al. 2021a, b).

Geological engineering

Stabilizing geological bodies

The slopes can become unstable due to a combination of seepage and external loading (Vanicek and Vanicek 2008; Gong et al. 2019; Conte et al. 2019; Li et al. 2019). Before and during construction, soil stabilization is often considered at or from the surface to improve the inadequate soil conditions to meet the requirements of earth structure construction. The approaches of soil stabilization include compaction, installing nails, sheets or piles, or mixing the soil with lime or cement (Karol 2003), the majorities of which require substantial energy for material producing or installing (DeJong et al. 2010). There is a clear potential for the use of energy-saving technology for stabilization of geological bodies and MICP is evidently such an alternative for approaches mentioned above.

A few field trials have been performed in which MICP have been used for soil stabilization. A MICP treatment was designed for gravel stabilization to enable horizontal directional drilling (HDD) for a gas pipeline in the Netherlands (van Paassen 2011). A 1000 m^3 volume at depths from 3 to 20 m below the surface was treated (Fig. 15). The treatment involved an injection of 200 m^3 bacterial suspension cultivated in the laboratory, two injections of 300 ~ 600 m^3 reagent solution containing urea and calcium chloride. Then groundwater was extracted until electrical conductivity and ammonium concentrations returned to background values. The large-scale MICP treatment was a success, since HDD was possible in the loose gravel deposit without instability. Gowthaman et al. (2019) found that the bacteria (*Lysinibacillus xylanilyticus*) isolated from the subarctic cold region had a significant potential to produce urease enzyme at temperatures 15 ~ 25 °C. They applied the bacteria for slope stabilization in a model solidification test, suggesting MICP compatibility in subarctic cold climatic regions. Hata et al. (2020) proposed a bio-mediated treatment to reinforce the

(a) (b) (c)

Fig. 15 (**a**) Cementing gravel for borehole stability; (**b**) The biocemented gravel borehole remaining stable after drilling through; (**c**) Calcium carbonate distributed throughout the gravel (van Paassen 2011) methane hydrate layers, using *Sporosarcina newyorkensis* with higher urease activities under low-temperature conditions, to make methane gas extraction safer and reduce sand production in the well, making extraction operations more efficient and cost effective.

It is appropriate to recommend MICP for slope surface stabilization, enhancing the surface cover condition of the slope and promoting high aggregate stability at the surface zone. Using surface percolation for treatment could strengthen the soil significantly by forming more effective crystals at free-draining conditions and can be highly applicable on unsaturated or partially saturated natural slopes and embankments (Cheng 2012). The surface percolation method can be applied to the soils by spraying, irrigating or trickling. These methods are simple and can decrease the cost of MICP by avoiding the construction of solution injection systems. It should be noted that fine content governs the behavior of slope soil significantly. It increases particle contacts by bonding with the sand grains and participates in the force chain of the treated matrix. It provides the matrix support effectively by facilitating the formation of bridges between carbonate crystals. Nevertheless, fine content tends to filter more bacteria at surface zone of slope and results in high cementation at the surface level and reduction in carbonate precipitation along the profile (Gowthaman et al. 2019). Thus, applying MICP for soil stabilization actually requires a balance between the support from the fine content and the negative filtering effect caused by it.

Improving soil thermal conductivity

Geothermal energy is a clean, renewable and sustainable energy resource, and it can be exploited and utilized by various underground energy geo-structures like ground source heat pumps (GSHPs), geothermal energy piles (GEPs), etc. (Laloui and Di Donna 2013). The performance of the energy geo-structures is strongly affected by the saturation conditions of soils (Venuleo et al. 2016), because moisture content is the primary influence factor of soil thermal conductivity compared with other factors such as mineralogical component, dry density, etc. (Zhang and Wang 2017). The heat exchange efficiency of saturated soils was increased by 40% compared with that of dry soils (Choi et al. 2011). Apparently, greater soil moisture content leads to higher heat exchange efficiency. As a result, energy geo-structures are applicable in temperate or subtropical areas but still undeveloped in arid environments because of the low saturation conditions of soils.

A way for improving soil thermal conductivity is to expand the contact area between soil grains and make it a good conductor of heat. MICP is an ideal process for realizing this purpose among soil grains. Venuleo et al. (2016) investigated the effect of MICP treatment on soil thermal conductivity and found a significant improvement of the thermal conductivity of soil especially for low degrees of saturation. Thermal conductivity of MICP treated soils was increased by 250% as compared with the untreated soils. This enhancement is attributed to the mineralized calcite crystals acting as 'thermal bridges' between the soil grains (Fig. 16), offering a larger surface area for heat exchange compared with the untreated material in which exchanges occur through smaller contact points. Using the MICP technique not only increased the thermal conductivity of sands (Wang et al. 2019). but also reduced the influence of saturation degree on sand thermal conductivity (Ding et al. 2019), extending geothermal applications in arid areas. The MICP technology could significantly improve the thermal conductivity of soils and the overall heat transfer efficiency, particularly at low saturation degrees or nearly dry conditions. Hence, it is feasible and advantageous to use MICP-treated

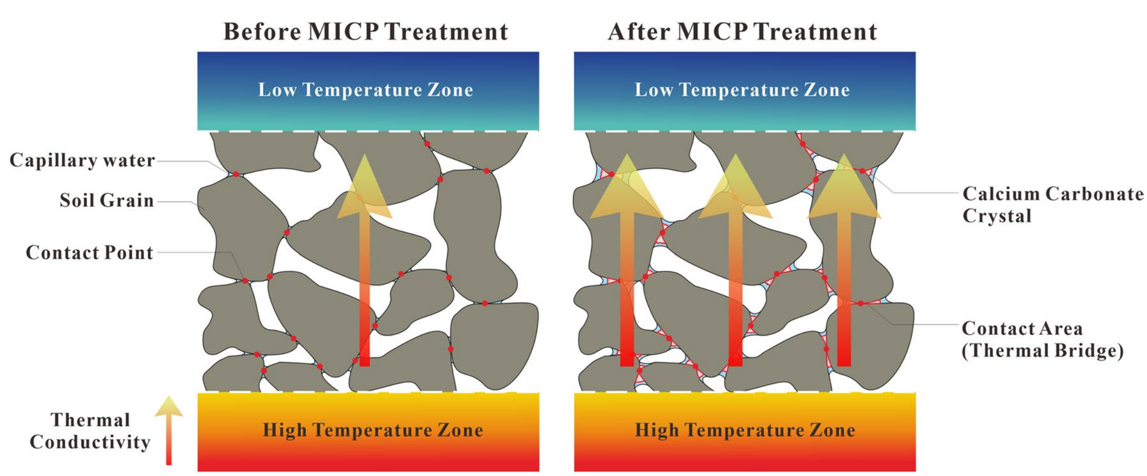


Fig. 16 Schematic representation of the thermal conduction through soil grains (left: the case of untreated soil; right: the case of MICP-treated soil due to the presence of calcium carbonate crystals bridging the soil grains and redistribution of capillary water)

soils as enhanced grout materials for underground energy geo-structures, potentially expanding geothermal applications in arid areas. The possible challenge for this application might be survival and activity of microorganisms in harsh arid environments.

Problematic soil treatment

Studies of soil improvement by MICP have focused primarily on sandy soils from aforementioned literatures. But for problematic soils faced by civil infrastructures, like clayey soils with varying plasticity characteristics, the related studies are still limited (Kannan et al. 2020; Xiao et al. 2020; Teng et al. 2021). These soils are common in the majority in the land areas of different countries. It would be beneficial to use MICP as a technique for modifying these soils which show prevalence and bring costly damages. A paradox should be noted that although MICP is more effective in case of soils containing higher clay contents due to the presence of higher bacterial populations within the clay fraction, higher clay contents will definitely reduce permeability, making percolation of treatment solutions slower and harder, thereby requiring a longer time for treatments (Islam et al. 2020).

A big challenge for tackling these soils containing high clay contents is their potential to grow cracks. The formation of desiccation cracks in bentonite soils is detrimental to the long-term performance of engineered clay barriers in geological storage facilities. Thus, mitigating the desiccation cracking potential or remediating the desiccation cracks in bentonite soils via MICP have been well discussed in recent years (Guo et al. 2018; Vail et al. 2019; Liu et al. 2020a). Moreover, Liu et al. (2020a) systematically investigated the effect of MICP treatment on clayey soil desiccation cracking behavior, and first quantified the relationship between the geometric parameters of crack patterns and MICP treatment cycles. This study is expected to improve the fundamental understanding of desiccation cracking mechanisms in the MICP-treated soils and provide insights into the potential application of MICP for cracking remediation in clayey soils. Clayey soils mixed with grains of different sizes were improved through biocementation in many literatures (Cheng and Shahin 2015; Cardoso et al. 2018; Li et al. 2018a). Other specific types of problematic soils like tropical residual soil (silt, ML) (Soon et al. 2014) and coal (Song and Elsworth 2018) were also taken into consideration. Additionally, indigenous bacteria can possibly be used to stabilize clayey soils of varying plasticity. There was an increase in the LL (Liquid limit) and PI (Plasticity limit) of the treated soils, but it did not adversely impact the swelling or strength behavior of the treated soils (Islam et al. 2020). While further tests and analysis on this approach are in need, MICP using biostimulation can increase the strength of clayey soils and additional treatment cycles may increase strength beyond threshold levels for stabilizing subgrade (Islam et al. 2020; Kannan et al. 2020; Xiao et al. 2020).

New perspective: mitigating geological disasters

Geological disaster (i.e. landslide and debris flow) usually results in significant impact on human activities, either through loss of life or injury, or through economic loss (Fan et al. 2018; Domènech et al. 2019; Juang et al. 2019a, 2019b, 2022; Tang et al. 2019; Gong et al. 2021). Based on previous studies, it is reasonable to envisage that the MICP technology could be used in more practical conditions. At present, there is no explicit report on the application of the MICP technology in preventing and controlling geological disasters. But the superior performance in the reinforcement of rock and soil via MICP is expected to provide a new solution

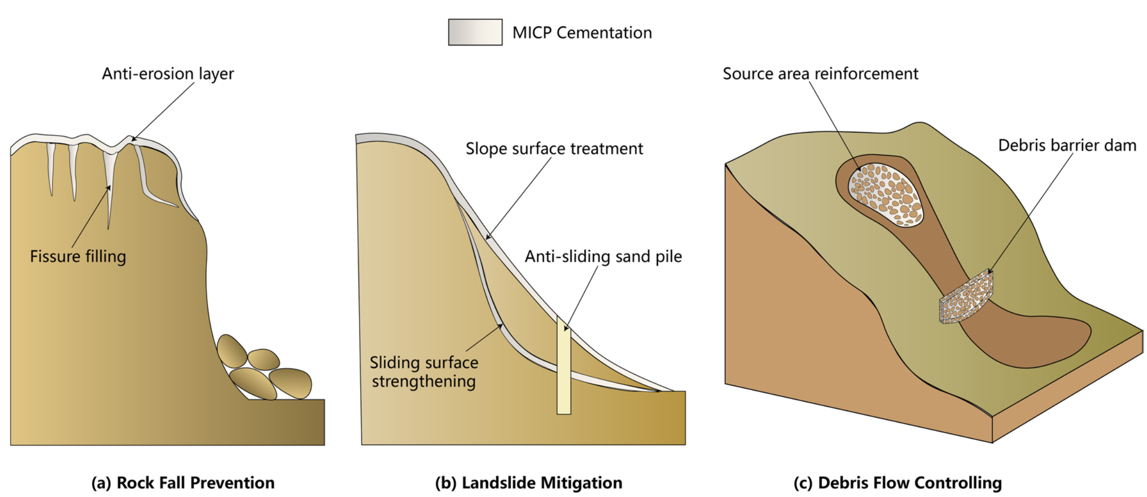


Fig. 17 Prevention and controlling of geological disasters by MICP treatment

for mitigating these disasters. Improving soil liquefaction resistance under the action of earthquake and other external forces is an apparent advantage brought by MICP in the conception of disaster alleviation. It means the potentials of the MICP technology have not been seriously and systematically considered yet.

For example, in the aspect of rock fall prevention (Fig. 17a), microbial grouting can be used to repair the fissures of rock and soil mass at the top of the slope and improve its overall mechanical strength, so as to significantly reduce the risk of the rock and soil unit separated from the matrix under the action of external forces such as earthquake. At the same time, the MICP technology can also be used to treat the surface of rock and soil to form an anti-erosion layer to cope with weathering due to climate change, thus avoiding the invisible risk of collapse on steep slopes.

In response to landslide disasters (Fig. 17b), microbial grouting can be designed to strengthen the sliding surface, weak structural surfaces and other potential sliding surfaces to avoid secondary sliding. Then, the MICP technology combined with spraying technology is appropriate to treat the slope surface. After treatment, a layer of dense $CaCO_3$ protective layer with low permeability is formed on the slope surface, so as to reduce the rainfall infiltration, achieve the purpose of water diversion and avoid the weakening of rock and soil composing the slope. For large-scale slopes with sliding risk, anti-sliding sand piles should be set at the foot of the slope for protection. After filling sand in the pile foundation pit, microbial grouting can be used to reinforce the sand in the pile foundation, so as to significantly enhance the anti-sliding force of the slope, thus reducing the risk of sliding.

In addition, the MICP technology has a good prospect in debris flow controlling. As shown in Fig. 17c, the microbial grouting can cement and then reinforce the loose debris in the source area, enhance its resistance against rainfall erosion and reduce the risk of debris flow from the forming period. At the same time, using the MICP technology to cement local clastic materials, and setting up a barrier dam in the valley can play a role of retaining sediment and reducing the scale of debris flow.

Environmental engineering

Fugitive dust control

Airborne dust and debris from building materials (concrete, sand, etc.) often not only damage construction equipment but also present a major health hazard. The traditional dust suppression methods including spraying water, salts, chemicals, and petroleum products onto sources of airborne dust particles are well studied (Bolander and Yamada 1999). But most of them pose a potential environmental hazard. For example, Calcium chloride ($CaCl_2$) is commonly applied to unpaved roads to increase the dust suppression effort (Lohnes and Coree 2002). However, at such high concentrations, calcium chloride is extremely corrosive to metals and concrete. Comparatively, MICP is a potentially long-lasting, environmentally innocuous process that can be used to suppress dust from landfills, open pit mines, unpaved roads, and construction sites.

To evaluate the dust suppression effect of MICP on different soils and find an optimal formula of this technique, a large number of laboratory tests (Bang et al. 2009a, 2009b, 2011; Meyer et al. 2011) as well as some field applications were carried out. Gomez et al. (2014) carried out a field-scale, surficial application of MICP to improve loose sand deposits and provide surface stabilization for dust control and future re-vegetation. The most improved test plot received the lowest concentrations (Urea: 15 g/L, Calcium chloride 13.875 g/L) of urea and calcium chloride and developed a stiff crust measuring 2.5 cm thick, which exhibited increased resistance to erosion (Fig. 18). Naeimi and Chu (2017) used the MICP approach to reduce the percent of mass loss against erosive force of wind regarding to the

(a) (b)

Fig. 18 (**a**) Test plots established within a region of uniform, loose, poorly graded sand; (**b**) Thicknesses of cemented crusts measured by excavating cemented sand material. (Gomez et al. 2015) concentration and characteristics of aggregate used, climate, and traffic amounts. The results of this study showed that the required precipitation for dust control (70%) of sand is less than 15 g $CaCO_3/m^2$ between sand grains in bio-treated sand. Meng et al. (2021a, b) used MICP technology to control the wind erosion of surface desert soil. The optimal cementation solution (containing equimolar urea and calcium chloride) concentration and spraying volume were 0.2 M and 4 L/m^2, respectively. Under this condition, the soil crusts, with a thickness of 12.5 mm and a calcium carbonate ($CaCO_3$) content of 0.57%, remained intact on the surface of man-made mounds after being exposed to a 30 m/s wind for 2 min.

Also, when combined with flexible materials, the rigid connection made by MICP can further enhance material properties. Anderson et al. (2014) utilized MICP with fibers (hemp fibers or synthetic fibers) to bond soil particles together so that they were more resistant to becoming airborne. The soil samples treated with *S. pasteurii* formed a crust-like calcite-rich layer on the soil surface and that the addition of certain types of fibers further enhanced the effectiveness significantly. The amount of mass loss became virtually zero when 1.0 ml of medium containing bacteria (10^8 cells/ml) and fibers (0.25% of sand by weight) were added to 100 g of sand under a wind speed of up to 32 km/h applied for 2 min. Woolley et al. (2020) conducted tests to evaluate the effect of the addition of xanthan gum hydrogel (XEICP) in the treatment solution on the performance of a wind erosion-resistant crust formed using enzyme induced carbonate precipitation (EICP). Li et al. (2020) revealed combining MICP and Straw Checkerboard Barrier (SCB) technology, which are theoretically compatible and complementary to each other, for mitigating desertification should have promising outcomes by accelerating the process of sand fixation, vegetation restoration, and ecological restoration (Fig. 19).

Contaminated soil remediation

Heavy metal contamination of soils (and water) has become a serious issue to the environment and ecosystem health. The non-biodegradable nature of heavy metals leads to their accumulation of toxic levels which have resulted in destructive effects on human health as well as wildlife (Xiao et al. 2017). The release of heavy metals into the environment is typically associated with the discharge of the waste soils and wastewaters of many industries, including mining, tanning, pesticide production, and electroplating (Barakat 2011). Globally, there are millions of contaminated sites in which the soils are contaminated by the heavy metal(loid)s Arsenicum (As), Cadmium (Cd), Plumbum (Pb), Cobaltum (Co), Chromium (Cr), Hydrargyrum (Hg), Curium (Cu), Niccolum (Ni), Zincum (Zn), and Selenium (Se) with the present soil concentrations higher than the geo-baseline or regulatory levels (Wuana and Okieimen 2011).

Bioprecipitation by ureolytic bacteria is an appropriate strategy for refining heavy metals. Various studies have been carried out over recent years to remove toxic elements from soil and water such as As (Achal et al. 2012a), Cd (Zhao et al. 2017), Cr (Hua et al. 2007), Cu (Duarte-Nass et al. 2020) and Pb (Kang et al. 2014). High removal rate is set as a priority for these toxic ion removal processes via bioprecipitation according to recent studies (Table 5). Stimulating indigenous bacteria in contaminated soils also has a considerable potential for heavy metal removal (Kim and Lee 2019; Chen and Achal 2019). Several field experiments are reported on heavy metal remediation via MICP, revealing the possibility of its industrial application. Fujita et al. (2010) used ureolytically driven calcite precipitation and strontium coprecipitation for remediating 90Sr contamination at the Hanford 100-N Area in Washington. Xu et al. (2013) analyzed the effects of MICP on the soil near the concentration

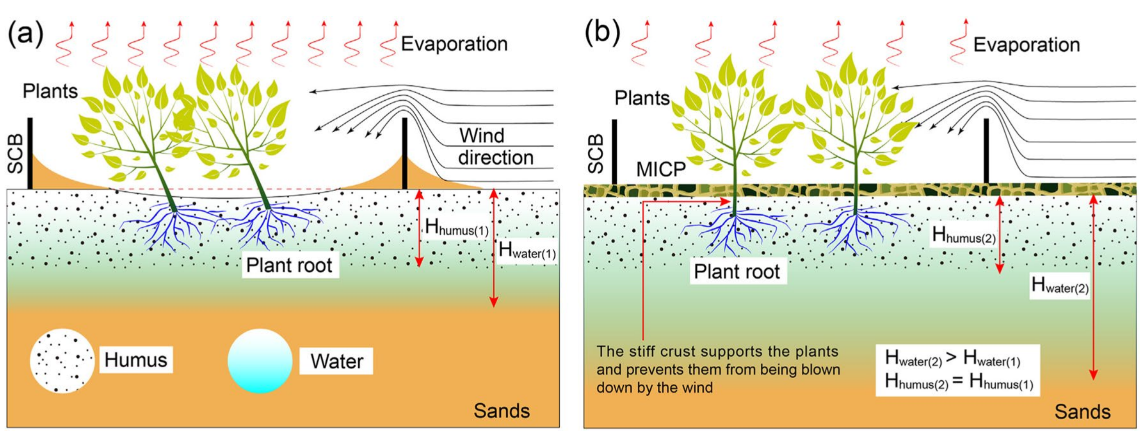


Fig. 19 Desertification control effect of grass grille combined with MICP: (**a**) Only grass grille for desertification control; (**b**) Grass grille and MICP for joint control (Li et al. 2020)

Table 5 Representative studies on heavy metal removal via MICP

Bacteria	Metal ions	Removal rate	Remarks	References
Sporosarcina pasteurii	Cu	10%	Low removal was due to Cu^{2+} complexation with the ammonia resulting from the hydrolysis of urea	Duarte et al. (2020)
Sporosarcina pasteurii	Pb	95%	*S. pasteurii* exhibited compatible resistance to Pb toxicity when its concentration was no higher than 30 mM	Juang et al. (2019a)
Stenotrophomonas rhizophila	Zn	96.25%	Although the *S. pasteurii* produced higher amounts of metal carbonates, the *S. rhizophila* and *V. boronicumulans* may be more effective due to the stability of them in high concentrations of Pb, Zn, and Cd	Jalilvand et al. (2019)
	Pb	71.3%		
	Cd	63.91%		
Variovorax boronicumulans	Zn	95.93%		
	Pb	73.45%		
	Cd	73.81%		
Sporosarcina pasteurii	Zn	98.71%		
	Pb	97.15%		
	Cd	94.83%		
Terrabacter tumescens	Ni, Cu, Pb, Co, Zn and Cd	90~99%	Heavy metal contaminants were efficiently removed both in soil and waste water	Li et al. (2016)
Lysinibacillus sphaericus	Cd	99.95%	–	Kang et al. (2014)
Sporosarcina koreensis	Cu and Pb	88%~99%	The bacteria could resist the acidity at pH higher than 1.5	Li et al. (2013)
Sporosarcina sp.	Co and Zn			
Terrabacter tumescens	Ni and Cd			
Kocuria flava	Pb	83.37%	Pb was also chelated with the MICP product	Achal et al. (2012b)

plant, while the contents of exchangeable As, Pb, Cd, Zn and Cu contents were 14.01, 4.95, 0.64, 33.46 and 12.95 mg/kg, respectively. After the treatment, the contents of exchangeable heavy metals in soil decreased obviously with exchangeable As, Pb, Cd, Zn and Cu of 2.37, 1.25, 0.31, 16.67 and 3.42 mg/kg, respectively. Plus, a consolidated structure like bricks was produced from chromium slags by Achal et al. (2013b) to facilitated the remediation of Cr (VI). They used ureolytic chromate reducing *Bacillus sp.* to facilitate calcite deposition on the Cr slag surface, thus reducing the permeability as it serves as a barrier to harmful substances to enter. The products were resistant to erosion by rainfall, thus preventing water to get contaminated with Cr (VI) pollution. Nevertheless, the long-term effects of the contaminated environment on different bacteria are still ambitious. A complete life-cycle analysis is necessary for the microorganisms affected by heavy metal ions and an ecological

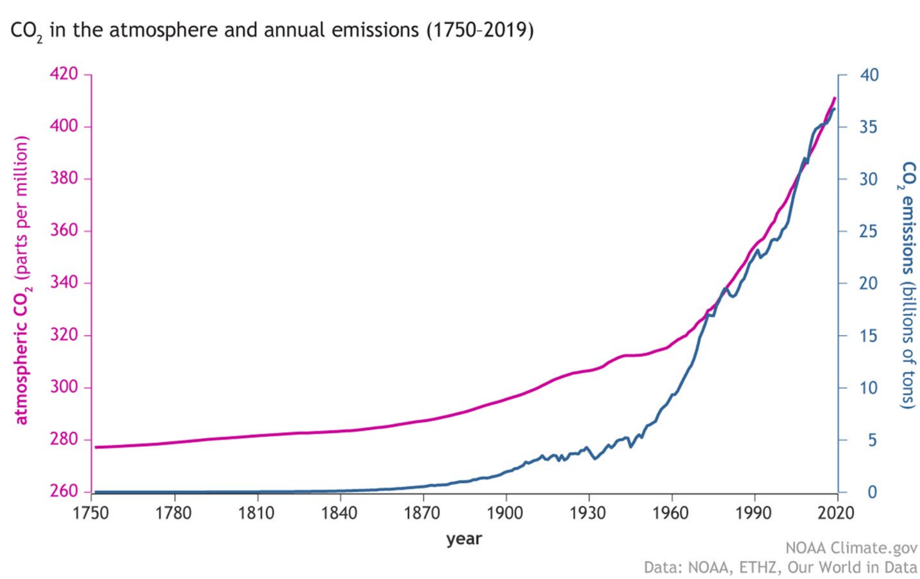


Fig. 20 CO_2 in the atmosphere and annual emissions (1750–2019) (NOAA Climate.gov graph, adapted from original by Dr. Howard Diamond (NOAA ARL), atmospheric CO_2 data from NOAA and ETHZ, CO_2 emissions data from Our World in Data and the Global Carbon Project)

perspective should be added when using MICP to treat heavy metal contaminated soils.

Carbon capture and storage

Currently, the concentration of CO_2 in the earth's atmosphere is about 415 ppm; however, this is increasing at approximately 2 ppm/year (Fig. 20). Global climate change due to increasing emissions of CO_2 has attracted wide concern and scientists are seeking appropriate mechanisms to sequester CO_2. One method for decreasing the atmospheric CO_2 concentrations is converting the CO_2 into carbonate minerals, because these minerals are geologically stable (Ramanan et al. 2009). One major issue for this spontaneous chemical carbonate mineral formation is that this process tends to have slow reaction rates and is highly dependent on pH (Zhu and Logan 2014). Naturally, CO_2 is sequestered by chemical fixation of CO_2 in the form of carbonate such as calcite, aragonite, magnesite and dolomite, but the reaction rate is very slow (Dhami et al. 2013). MICP, on the other hand, has recently been suggested safer, more eco-friendly and more efficient, in CO_2 sequestration (Okwadha and Li 2010). Okyay and Rodrigues (2015), and Okyay et al. (2016) investigated the potential of MICP in CO_2 sequestration to reduce the atmospheric CO_2 levels. In their study, two possible mechanisms for can be removing CO_2 from the atmosphere have been carefully analyzed: (a) sequestration by MICP biotically; (b) sequestration by increasing the environment pH (i.e., CO_2 solubility) abiotically. CO_2 sequestration through MICP process is directly related to bacterial community composition and abiotic factors, such as pH and growth media. In consortia with low diversity, the CO_2 sequestration is much higher than in very diverse consortia. Species from the genera *Sporosarcina, Sphingobacterium, Stenotrophomonas, Acinetobacter,* and *Elizabethkingia* may play an important role in CO_2 sequestration. Until now, relevant research is still scarce and limited in the initial stage. Using MICP in CO_2 sequestration needs to be thoroughly and systematically discussed as part of the possible sequestration solution for tackling climate change.

Future opportunities and challenges

After reviewing existing and envisioned applications of the MICP technology through existing studies, a new perspective is formed on the feasibility and difficulties of this technology for engineering practice. The MICP treatment appears promising to provide reliable solutions for various engineering problems in the background of frequent and intense human activities. This review has figured out the following opportunities and challenges that necessitate further research efforts in MICP:

Opportunities

(1) As main entities over the world began to regain courage and reunite around 'The Paris Agreement' in 2021, innovation and revolution for tackling climate change will be urgently demanded. Generally considered as green engineering technology, the MICP technology will come into a 'new spring' towards a wide range of applications with the goal of replacing traditional energy-intensive and low-efficient technologies.

(2) Through the detailed fundaments and applications discussed, the MICP treatment generally appears a fast, deployable and non-disruptive method which can easily meet different scales or requirements depending on engineering conditions. There is no need for large machinery and no restrictions on the engineering site. Therefore, MICP is an ideal strategy adapting to complex environments and an effective supplement for existing physical, chemical and plant-based strategies.

(3) Bio-augmentation is generally considered to yield higher reaction rate than bio-stimulation, while bio-stimulation can overcome some drawbacks of bio-augmentation (e.g., considering cost and processes associated with culture of required micro-organisms). Bio-stimulation can be further divided into ex-situ bio-stimulation and in-situ bio-stimulation. Ideal pathways for MICP should reach a compromise between these choices and a combination of their main advantages.

(4) It seems plausible that MICP can simultaneously provide multi-functional solutions if appropriate bacteria (or microbial consortia) are selected. The mechanism of MICP in cracks of various materials, combined with proper auxiliary additives, vividly shows its potential as a versatile technique. And it should be noted that MICP evidently influences the properties of materials including strength, dynamic response, permeability, thermal conductivity, durability etc., at the same time, though some studies are at a preliminary stage.

(5) We are still far from a comprehensive understanding of the underlying processes controlling the MICP technology. Better understanding of the multi-field coupling and multifunction of this technology requires more education and training on the fundamental knowledge and skills, which will boost the development of interdisciplinary/intersectional science and social collaboration. At least, effective assessing (e.g., dynamic testing platforms), monitoring (e.g., real-time sensors) and simulation (e.g., artificial intelligence) facilities or

methods are in need for analyzing, controlling and predicting the MICP process.

Challenges

(1) The post-COVID-19 world tends to re-examine the safety and reliability of biotechnologies. Thus, it is surely necessary to be circumspect and evaluate the ecological balance changed by the MICP process properly. Although studies to investigate microbial dynamics during MICP implementation have started (Gat et al. 2016), a mature life-cycle analysis from an ecological perspective is not yet available and the capability of MICP-treated materials to sustain life is unclear (Jiang et al. 2020). And a better restriction should be obtained on the bio-geochemical processes of MICP in order to achieve controllable engineering performances.
(2) Although ongoing MICP researches have already noted the significance of the durability (e.g., under freeze thaw cycles) of modified materials, possible long-term deterioration of MICP-treated materials is still overlooked. The degradation of engineering performance should be fully evaluated over long time scales and under severe adverse environments, which decides the feasibility of MICP for the future. The survival and activity of microorganisms in harsh environments are equally important (Rahman 2020), especially for those conditions requiring autogenous microbial reaction.
(3) While ureolysis process is the most popular to achieve MICP, it generates high-concentration ammonium ion and ammonia (incomplete reaction) as by-products, which is likely to harm environments and human health. Researchers have already considered alternative harmless MICP processes (e.g., iron reduction). But it is still unclear currently whether these alternative processes are technically feasible for applications. Further collaborations among geochemists, microbiologists, ecologists and engineers are required towards this direction.
(4) The uniformity of treatment effect is still a big challenge for the application of MICP in practical engineering, especially when it comes to large-scale or field-scale occasions. To solve the problem of heterogeneity, Cheng et al. (2019) and Wang et al. (2018b) proposed lowering the pH value or the temperature of the bacterial solution to delay the microbial mineralization reaction, respectively. But these studies only hold rational at a relatively experimental or preliminary stage.
(5) Further efforts are needed for decreasing the cost and energy consumption (e.g., producing chemical substrates) of the MICP technology, especially facing the capital-cost driven construction industry. Much attention should be paid to utilizing industrial by-products or wastes and non-sterilized media as alternatives.

Summary

In this work, five main fields involving 15 specific engineering applications of the MICP technology are reviewed. When studying the feasibility of MICP in various fields, the paper discusses fundamentals of this technology in practical situations. The obtained main conclusions related to each area of engineering are summarized as follows:

(1) Geotechnical engineering: as the greatest research focus, geotechnical engineering applications of MICP call for comprehensive improvement of static and dynamic characteristics of geomaterials. To enhance the bearing capacity of soil, bioaugmentation, biostimulation and enzymatic approaches are carefully compared, focusing on the compressive strength of treated soil and upscaling potentials. On the contrary, strength becomes a minor factor for resisting soil liquefication because a “dense sand like” behavior is able to avoid liquefication under an earthquake, which means fewer treatments, less material and a smaller investment in MICP.
(2) Construction materials: MICP can help produce eco-friendly and durable building materials. Incorporating bacteria into the production of materials and external bio-treatment for existing materials are two main attempts towards improving the properties (e.g., strength and durability) of construction materials. The external remediation techniques for concrete/cement may differ according to the size of fissures. The conception of incorporating microorganisms into the mortar is further developed into self-healing building materials relying on the survival of bacteria in the harsh environment, which can be realized through immobilization of microorganisms in homogeneous media or compressing bacteria and nutrients directly into a capsule.
(3) Hydraulic engineering: MICP is a promising and cost-efficient technology in preserving water resources and even subsurface fluid under the circumstance of unconventional oil and gas exploitation, CO_2 geological storage and nuclear waste disposal. Both carbonate precipitation clogging and biofilm clogging serve the purpose of reducing permeability. Simulation is necessary for predicting and analyzing the biosealing process. Meanwhile, piping, internal erosion and surface erosion are common hydraulic engineering problems that could be addressed by MICP. This surface soil treatment can be coupled with other additives, which may expand its utilization even to ancient clay buildings.

(4) Geological engineering: in the field of geological engineering, stability of geological bodies is a big concern because of the external disturbance caused by human engineering activities. MICP has been proved as a compatible technique for stabilizing soils. Surface percolation appears to be a simple but wise choice for applying this technique. The MICP treatment is outstanding in dealing with problematic soils like bentonite soils or even coal. Based on these studies, MICP is further envisioned to mitigate geological disasters like landslide and debris flow. It is also noteworthy that MICP can obviously improve the thermal conductivity of soils, particularly at low saturation conditions.
(5) Environmental engineering: three main problems facing the global environment including fugitive dust, contaminated soil and climate change are raised up and typical engineering measures for palliating and even removing possible hazards are discussed. MICP, as an environmentally innocuous and multi-scale available process, seems versatile in fixing and suppressing dust, precipitating heavy metal ions and sequestrating CO_2 geologically. Although relevant studies are in the initial stage, we can expect more breakthroughs in efficiency and economic feasibility of MICP to make it friendly and reliable for human and wildlife in the future.

MICP is a mainstream engineering technology for the future, with its advantages in carbon footprint benefits, multi-functionality and convenience. Opportunities and challenges coexist for this technology where ecological balance, environmental impact and industrial applicability should be predominant considerations.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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